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The Fast Propagation of Messages in VANETs and the Impact of Vehicles as Obstacles on Signal Propagation

Zengzhe Zhang



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Abstract

Vehicular Ad hoc NETWORKS (VANETs), an emerging technology, use vehicles as nodes to form a mobile ad hoc network for the dissemination of safety and entertainment messages. The thesis provides a scheme for the fast propagation of messages in VANETs and evaluates the impact of vehicles as obstacles on signal propagation.

An improved scheme for intermediate node selection in DBA-MAC (Dynamic Backbone Assisted MAC) is proposed, which consists of a CW (Contention Window) constraint scheme and an updated criterion of suitability. A performance comparison shows that messages in the proposed scheme propagate faster than in DBA-MAC. The CW constraint scheme is also applicable in VANET protocols which adapt the CW mechanism to communicate the suitability of vehicles for acting as intermediate nodes. Additionally, the mathematical models for DBA-MAC and the proposal are established, which indicate the probability of candidates to be chosen over alternatives in the intermediate node selection.

A novel metric - delay taking into account the effect of formation time (DEFT) - is proposed. DEFT combines the network formation time and propagation delay. It shows the impact of network formation on propagation latency. The configuration for optimal performance can be acquired using the proposed DEFT. In order to evaluate the proposals, a novel distribution of vehicle location is proposed. In the proposed distribution, the security distances between adjacent vehicles in the same lane are considered. The estimation of vehicles' location can be more practical and accurate using the proposed distribution.

In the wide body of the VANET literature, it is assumed that all the vehicles within the radio range of a transmitter are able to receive the signal. Yet, in practice, the vehicles as obstacles between the transmitter and the receiver affect the signal propagation significantly. This thesis presents the impact of these obstacles on the network connectivity and system performance of the protocols. The results and the analysis show that neglecting obstacles in practice leads to a significant degree of error in the estimation of system performance. In practice, tall vehicles forward messages in a more efficient way than do lower vehicles since they are free from the obstacle effect. An improved scheme is proposed, in which the height of vehicles is used as a factor to determine their suitability for message forwarding.

Declaration of originality

I hereby declare that the research recorded in this thesis and the thesis itself was composed and organised by myself in the School of Engineering at The University of Edinburgh, except where explicitly stated otherwise in the text.

Zengzhe Zhang

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Acronyms and abbreviations

ACK	Acknowledge message
AODV	Ad hoc On-Demand Vector
AP	Access Point
BBR	Border node-Based Routing
BEB	Binary Exponential Backoff
BG MSG	Background Message
BM	Backbone Member
BSS	Basic Service Set
BSSID	Basic Service Set Identification
CDF	Cumulative Distribution Function
CH	Cluster head
CMH	CWC + MDC + Height consideration
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTS	Clear-to-Send
CW	Contention Window
CWC	Contention Window Constraint scheme
CWCMD	CWC + MDC
DA	Destination Address
DBA-MAC	Dynamic Backbone-Assisted MAC
DCF	Distributed Coordination Function
DEFT	Delay taking into account the Effect of Formation Time
DIFS	DCF Interframe Space
DS	Distribution Service
DSR	Dynamic Source Routing
DSRC	Dedicated Short Range Communications
DUR	duration of the frame
ED	Exponential Distribution
ErD	Erlang Distribution
ESC	Enhanced Spring Clustering

ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
FC	Frame Control
FCC	Federal Communications Commission
FCS	Frame Check Sequence
FSPL	Free space path loss
GEV	generalised extreme value
GH	group head
GPS	Global Positioning System
GPSR	Greedy Perimeter Stateless Routing
IBSS	Independent BSS
ID	identity
ITS	Intelligent Transportation System
ITU-R	International Telecommunication Union-Radiocommunications
K-S test	Kolmogorov-Smirnov test
LOS	Line of Sight
MAC	medium access control
MANET	Mobile Ad Hoc Network
MDC	Minimum Distance as Criterion of suitability
MTR	maximum transmission range
NAV	Network Allocation Vector
NM	Normal Member
PAODV	Prior AODV
PDF	Probability Density Function
PDR	Packet delivery ratio
QPSK	Quadrature phase-shift keying
RA	receiving station address
RR	Radio Range
RREP	route reply
RREQ	route request
RSSI	Received Signal Strength Indicator
RSU	Roadside Unit
RTS	Request-to-Send

ROI	Region of interest
Rx	receiver
SA	source address
SB	Smart Broadcast
SCF	Store-Carry-Forward
SCH	secondary CH
SD	Security Distance
SEQ	sequence control
SI	Suitability Index
SIFS	Short Interframe Space
SSID	Service Set Identification
STA	station
TA	transmitting station address
TTL	time-to-live
Tx	transmitter
V2I	vehicle to infrastructure
V2V	vehicle to vehicle
V2X	vehicle to roadside unit
VANET	Vehicular Ad Hoc Network
VD	Vehicle Density
WAVE	Wireless Access in Vehicular Environments
WBSS	WAVE BSS

Nomenclature

α	parameter of impact of network formation on propagation delay
ΔCW_{ik}	gap of CW between candidate i and k
Δh	height gap of LOS and the obstacle
ΔLN	gap of lanes between Tx and Rx
Δs_i	distance between candidate i and last BM
Δv_i	speed gap between candidate i and last BM
λ_p	wavelength in the working frequency f_p
μ	the mean of height of the obstacle
μ_k	the mean of height of the k th obstacle
σ	the standard deviation of height of the obstacle
σ_k	the standard deviation of height of the k th obstacle
A_{fs}	free space path loss
C_l	speed of light
CW_i	maximal countdown number of candidate i
CW'_i	a randomly-selected value from CW_i to 0
d_c	critical range of transmission
d_{TR}	distance between Tx and Rx
d_{obs}	distance between Tx and the obstacle
d_{obs1}	distance between Tx and the 1st obstacle
d_{obs2}	distance between Tx and the 2nd obstacle
$ErD(x, n)$	Erlang distribution of the n th following vehicle in distance x
$F_a(x)$	CDF of location distribution of the vehicles ahead of another vehicle
$F_f(x)$	CDF of location distribution of the vehicles following another vehicle
f_p	working frequency
$f_s(n, x)$	PDF of the location distribution of the n th following vehicle on the same lane
$F_s(n, x)$	CDF of the location distribution of the n th following vehicle on the same lane
$f_d(n, x)$	PDF of the location of the n th following vehicle on a different lane
$F_d(n, x)$	CDF of the location of the n th following vehicle on a different lane
h	height of LOS at the location of the obstacle

h_k	height of LOS the location of the k th obstacle
h_{Rx}	height of Rx
h_{Tx}	height of Tx
k_{ij}	Coulumb's constant between vehicle i and j
L	length of CW selection
L_{ACK}	length of ACK message
L_{bgmsg}	length of background message
L_{candi}	length of candidature message
L_{smmsg}	length of safety message
$N_{sl}(x)$	number of potential vehicles on the same lane of the reference vehicle in the range x
$N_{dl}(x)$	number of potential vehicles on a different lane of the reference vehicle in the range x
ON_s	obstacle number as Tx and Rx on the same lane
ON_a	obstacle number as Tx and Rx on the adjacent lanes
ON_o	obstacle number as Tx and Rx neither on the adjacent lanes nor on the same lane
P_c	connection probability
P_i	winning probability of candidate i in BM selection
R_b	transmission bit rate
r_{ij}	distance between vehicle i and j
SI_i	suitability index of candidate i
T_{ACK}	transmission time of ACK by a BM
$T_{backoff}$	backoff time before message transmission
T_{delay}	propagation delay of a safety message in 1 km
T_{dft}	the proposed delay with formation time
T_{ft}	average formation time of 1-km BM network
T_{pre}	waiting time of safety message generator before broadcasting the message
T_{slot}	time period of a slot
T_{tx}	transmission time of a safety message

Chapter 1

Introduction

1.1 VANET

Vehicular Ad hoc NETworks (VANETs), a special type of Mobile Ad hoc NETworks (MANETs), encompass vehicular communication. Differently to cellular networks, VANETs conduct communication with no help from traditional infrastructure. VANETs are categorised into two basic types; vehicle-to-roadside-infrastructure (V2X) and vehicle-to-vehicle (V2V). A V2X network provides the vehicles, which are connected to roadside infrastructure, e.g. traffic lights and road lights, with access to the Internet, while in V2V operation the vehicles organise the network and share information with no central control.

According to the type of information provided [3, 4], VANET applications are divided into two types: safety and infotainment. Safety applications include information on traffic conditions, e.g. traffic collisions, congestion, emergency vehicle warnings, overtaking vehicle warnings, lane changing assistance or pre-accident warnings. Safety applications of VANETs inform drivers of any change in traffic conditions and take corresponding actions. Infotainment, the portmanteau word of information and entertainment, provides drivers with locale-based services, e.g. points of interest notification, and media downloading, information sharing among vehicles and Internet access.

The US Federal Communications Commission (FCC) allocates the 75 MHz spectrum in the 5.9 GHz band exclusively to vehicular applications and research in the Dedicated Short Range Communication (DSRC) was launched in 1992 [5]. Since 2004, the focus of research on vehicular network has migrated to the auspices of the IEEE standard group. IEEE 802.11p is the amendment to the 802.11 standard on data links and physical layers for vehicular environments, the latest version of which was released in 2010 [6]. IEEE Task group 1609 undertook the work of developing specifications for vehicular networks at the application and network layers, and establishing the IEEE 1609 standards set [7].

1.2 Thesis Organisation and Contribution

This thesis investigates the fast propagation of messages in VANETs. Based on a cross layer protocol Dynamic Backbone-Assisted MAC (DBA-MAC) [16], an improved scheme is proposed to achieve better performance of propagation. In addition, the impact of vehicles on signal propagation, on network connectivity and system performance is also studied.

Chapter 2 introduces the background knowledge of the thesis. The discussion includes the features of VANETs which distinguish VANETs from MANETs, IEEE 802.11p, i.e. the dedicated protocols for vehicular networks, a summary of routing protocols in VANETs, and the factors related to network connectivity.

Chapter 3 introduces a cross-layer protocol, DBA-MAC, which works in both proactive and reactive modes. Analysis shows its potential to enhance system performance in terms of propagation delay and the number of vehicles involved in DBA-MAC communication. Based on the analysis, an improved scheme is proposed, the Contention Window Constraint and Minimum Distance as criterion of intermediate node selection (CWCMD). The CWCMD contains a novel criterion for intermediate node selection and a contention window (CW) constraint scheme. The CWCMD is also applicable to other VANET protocols that adapt the CW mechanism to distinguish between vehicles [57, 81]. The CWCMD is shown to improve upon DBA-MAC and flooding and provides faster propagation.

In Chapter 4, the mathematical models of DBA-MAC and the CWCMD are established based on statistical analysis. The models are used to predict and estimate the system performance of intermediate node selection which is the key factor in propagation performance, as well as key to validating the simulation results. For the proactive protocols, commonly-used metrics, i.e. delay and overhead/formation time, show the network performance of delay and network formation time separately. A novel metric for proactive protocols is proposed. The proposed Delay taking into account the Effect of Formation Time (DEFT) combines the impact of network formation on propagation and propagation delay. By adjusting the CW-related parameters, the optimal performance of a system, in terms of the DEFT, can be achieved.

Vehicles between the transmitting vehicle and the receiver may block the line of sight (LOS) and attenuate the signal strength. In Chapter 5, the obstacle effect caused by such vehicles is analysed, with the impact on network connectivity and system performance of DBA-MAC

and the CWCMD. Analysis and simulation results show that vehicles between the transmitter and receiver affect signal propagation significantly and the performance trend, e.g. propagation delay, with vehicle density is opposite to the ideal case. Additionally, in existing literature the vehicles on the road are assumed to be following a Poisson distribution, yet simulation results indicate that the existence of a security distance between adjacent vehicles in the same lane leads to variation in location distribution. A novel distribution of vehicles is proposed in this chapter, which incorporates the security distance.

The contributions of this thesis are listed below:

- 1) An improved propagation scheme for fast propagation of messages in VANETs, based on DBA-MAC, is proposed. The CW constraint scheme and novel criterion of relay selection improve system performance in terms of propagation delay and average transmission time for each message;
- 2) The mathematical models are established, for both DBA-MAC and the CWCMD from statistical analysis. The models provide a tool to predict, estimate and validate system performance from simulation;
- 3) A novel metric for proactive protocols in VANETs, the DEFT, is proposed;
- 4) A distance distribution among vehicles is proposed, in which a security distance is retained between adjacent vehicles in the same lane. The proposed model provides a more practical distribution than the Poisson distribution, the widely adopted distribution in the existing literature.
- 5) The impact of obstacles caused by the vehicles between transmitter and receiver on network connectivity and system performance, e.g. delay, is presented and the necessity of considering obstacles in estimation of system performance in VANETs is also demonstrated;
- 6) An improved propagation scheme incorporating vehicles' height in the BM selection is proposed. The scheme is based on the proposal, the CWCMD, proposed in this thesis. The consideration of vehicles' height is to deal with the obstacle effect in practical traffic.

Chapter 2

Background

2.1 Features of VANETs

VANETs are a subset of mobile ad hoc networks (MANETs). They differ from MANETs as the nodes are vehicles, subject to current traffic conditions. They exhibit the following features [8, 9]:

1) High dynamic and frequent disconnection: due to the high speed movement of nodes (vehicles) in VANETs, compared with nodes in MANETs, the duration time of connection could be shorter than that in MANETs, which leads to more frequent breakage of links than in MANETs. Typically, the radio range is assumed to be 240m, which is the configuration in this thesis, and the gap in speed between two vehicles moving in the same direction is 10 mph, e.g., 50 mph and 60 mph, so the maximum connection time is approximately 107 s if the faster vehicle is catching up the other one from the very beginning. If they are moving in the opposite direction, the maximum connection time is less than 10 s. While for a relatively low-speed MANET, e.g. 1 m/s between two nodes, the connection duration could be as long as 480 s, approximately 4 times 109 s. Frequent disconnection of links in VANETs also leads to the frequent change of network topology. Frequent disconnection is an important factor in the design of protocols for VANETs.

2) Density variation: due to the mobility of VANETs, the density of vehicles varies with road condition and time. Traffic jams and accidents, especially in rush hours on weekdays, make the road congested to varying degrees. Vehicles may accumulate near traffic lights even in sparse traffic conditions. Usually in an urban scenario, vehicle density is higher than on a highway or rural scenario. Congestion in rush hours reduces highway efficiency, yet drivers can experience a relatively comfortable driving experience at other times of the day, especially at night when vehicles are sparse on the road. The vehicle density is related to the network connectivity of VANETs and may make an impact on the performance of communication schemes dedicated for VANETs.

3) Regular trace: in MANETs, nodes can move in any direction along an irregular trace. While in VANETs due to the confines of the roads, buildings and bridges, the traces of the nodes are regular, i.e., along the road. In addition, it is observed that the speed of a vehicle may be influenced by other vehicles on the road, especially in dense traffic. Therefore, the traces of nodes in VANETs are not completely independent. The traces of nodes may be predictable from the road maps and traffic conditions.

4) Power consumption of VANETs: in MANETs, power consumption is a crucial problem, since the carrier is usually a small device and the battery capacity for the sensor is limited. While in VANETs, network power is supplied by an on-board source, i.e. the vehicle battery which provides enough energy for the VANETs sensors, and power consumption is not an important problem.

5) Varying environment for communication: the impact of environment on the VANET system changes with the type of environment. Typically, two types of environment are considered in the application of VANETs, i.e., an urban scenario and a highway one. In the urban scenario, the vehicles move slower with more complicated traffic patterns, due to traffic lights and congestion. The buildings and traffic lights provide the potential for VANETs to form a vehicle-to-infrastructure network, as well as block radio propagation. In the highway scenario however, conditions are simpler, i.e., faster speed, mainly straight paths, less interference from roadside units. Due to the lack of roadside infrastructure, the communication between vehicles is mainly in the form of vehicle-to-vehicle.

2.2 IEEE 802.11p

IEEE 802.11p, *a.k.a.* Wireless Access for the Vehicular Environment (WAVE), is the communication protocol dedicated to Intelligent Transportation Systems (ITS). The application of WAVE in ITS includes the data exchange between vehicles on the move (V2V) and between vehicles and roadside units (V2X) in the frequency band 5.9 GHz, licensed by the US Federal Communications Commission (FCC) and European Telecommunications Standards Institute (ETSI). As an enhancement to IEEE 802.11 protocols, 802.11p has been standardised and the latest amendment version was released in 2010 [6].

The US Federal Communications Commission (FCC) and European Telecommunications Standards Institute (ETSI) allocated 75 MHz and 30 MHz of spectrum in the 5.9 GHz for DSRC,

respectively. The channel for DSRC consists of seven sub-channels with one control channel and six service channels.

Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) applications adopting DSRC can potentially reduce the possibility of traffic accidents by informing drivers of the real time traffic conditions. In addition, non-safety applications can also be provided via DSRC technology. Safety applications have higher priority than non-safety applications, and therefore they are the focus of vehicle technologies, aimed at saving lives by preventing accidents.

2.2.1 WAVE

2.2.1.1 Basic Service Set (BSS) and Basic Service Set IDentification (BSSID)

Two types of BSS [5], Infrastructured BSS and Independent BSS (IBSS), are defined in IEEE 802.11. In infrastructured BSS, a hub, called an Access Point (AP), is set for a group of stations. Through the AP, the stations in the group are able to connect to each other and access the source and services of the AP. To form the group, i.e. BSS, the AP broadcasts beacons. A radio registers for the group after several exchanges with the AP, e.g. authentication and association. The radios that do not participate in this are excluded from the group. In IBSS, no AP is appointed from the stations in the group, and the stations in the group communicate in an ad hoc manner. Different BSSs are connected to form an Extended Service Set (ESS).

A BSS is also known as a Service Set IDentification (SSID) and a Basic Service Set IDentification (BSSID). The SSID is the name of the BSS which is identified by the stations, the field being between 0 and 32 Bytes. The BSSID is the name of the BSS at the MAC layer and is 48-bits long. The stations in a BSS share the same, unique BSSID which is simply the MAC address of the AP.

Figure 2.1 presents the data frame of IEEE 802.11. The frame starts with a Frame Control (FC), indicating the type of the frame. DUR shows the duration of the frame, and overhead beyond physical transmission time if possible. The Frame Check Sequence (FCS) field is used to detect errors during transmission. Sequence control (SEQ) indicates the sequence number of each frame and fragmented frame. As is shown in Figure 2.1, at most 4 address fields are contained in one IEEE 802.11 data frame, which stores the source address (SA), destination address (DA), transmitting station address (TA), and receiving station address (RA) or BSSID. The type of address in each field is determined by the bits in the Frame Control (FC), which

indicate 'To DS' and 'From DS'.

FC	DUR	ADD ₁	ADD ₂	ADD ₃	SEQ	ADD ₄	DATA	FCS
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Figure 2.1: *Data frame in IEEE 802.11*

To detect whether a frame received is from the same BSS, the MAC level of a station checks the Address 1 field after receiving the frame. The comparison between the address in Address 1 and BSSID of the station tells it whether the frame is from the same BSS or not. This mechanism selects the frames of the same BSS among all the frames received.

2.2.1.2 BSS and BSSID in WAVE

The dynamic character of VANETs makes the access scheme in IEEE 802.11 relatively inefficient. Imagine a case where two vehicles are approaching each other from opposite directions in the different lanes. Due to the joint effects of the transmission range of wireless devices and the speed limit, the connection time can be in the order of seconds, while VANETs require immediate communication between vehicles, especially with regard to safety applications. The interactive steps as well as handshakes in group formation in IEEE 802.11 can be a barrier to meeting the requirement of VANETs [5].

A BSS in a vehicular environment is modified by the WAVE standard, i.e., WAVE BSS (WBSS). The on-demand beacon is broadcast by a station to create a WBSS. The beacon contains the information about the transmitter, e.g. service offered and configuration for the receiver to join. The receivers can decide whether or not to join in the WBSS based solely on the beacon received, without complex exchanges when the transmitter and receiver are on the same channel. The cancellation of interactions during network formation reduces the overhead of WBSS in fast movement environments. It is noted that a station belongs to a unique WBSS and it does not search the network to join another WBSS. Upon the establishment of a WBSS, every station in the WBSS, including the initial one broadcasting the beacon, has equal status and therefore the WBSS continues to work even if the initial station quits the network.

A special BSSID is defined in IEEE 802.11, the wildcard BSSID, the bits of which are all set to 1. IEEE 802.11p defines a WAVE mode, in which stations (vehicular nodes) in VANETs are

able to communicate by transmitting and receiving data frames with the wildcard BSSID. In WAVE mode, any station, no matter whether it is in a WBSS or not, is still able to broadcast or receive the message with a wildcard BSSID from nearby stations. This enables the safety messages in VANETs to propagate in an efficient manner.

2.2.2 Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA)

IEEE 802.11p adopts the identical medium access scheme in IEEE 802.11, CSMA/CA [11]. CSMA/CA allows the stations to share the same channel in an efficient manner. The summary of CSMA/CA is listed as follows:

- 1) the station with a frame to be transmitted senses the channel prior to transmission;
- 2) if the channel is idle, the frame is ready to be transmitted;
- 3) if the channel is busy, the station sets up a countdown step waiting for the idle status of the channel. The waiting time before transmission, i.e. backoff, is determined by the multiplication of a randomly-selected number and the duration of the time slot. The countdown begins as the channel is idle and pauses as the channel is busy again. When the channel is idle and the countdown reduces to zero, the frame is to be transmitted;
- 4) before the frame is transmitted, the station sends a Request-To-Send (RTS) packet and the intended receiver responds to the station with a Clear-To-Send (CTS) packet, which informs other stations in the same channel that a station is ready to send a frame and the channel becomes busy immediately. Application of RTS/CTS avoids possible collisions and partially solves the hidden-terminal problem;
- 5) Upon the completion of reception, the receiver sends an acknowledge (ACK) packet to the transmitter to inform it that the frame has been successfully received;
- 6) if the transmitter fails to receive an ACK after transmitting the frame, a re-transmission is executed after a random backoff time.

2.2.3 Distributed Coordination Function (DCF)

DCF, based on the CSMA/MA MAC protocol, is a basic method of random access in IEEE 802.11 [12]. The stations (STAs) in DCF are able to sense whether the channel is idle or busy, i.e., whether the signal strength received from the channel exceeds the threshold of the receiver or not.

Before a message is to be transmitted by an STA, the STA first checks the status of the channel for a period of Distributed InterFrame Space (DIFS). If the channel is idle for the period of DIFS, the STA starts transmission. Once the channel is busy, either before DIFS or during DIFS, the STA defers the transmission, checks the channel continuously and waits until the ongoing communication in the channel ends. STA starts transmission only after the channel remains idle for a period of DIFS. In this case, the STA generates a random waiting time before transmission. The waiting procedure proceeds to the end and then the STA transmits the message if the channel remains idle. Otherwise, as the channel turns to busy, the STA pauses its waiting procedure, and resumes after the channel is released.

DCF adopts the Binary Exponential Backoff (BEB) scheme to decide the waiting time prior to transmission. The product of a randomly-selected value from 0 to CW_i , CW'_i , and slot time is used as the waiting time, or backoff time $T_{backoff}$,

$$T_{backoff} = T_{slot} \cdot CW'_i \quad (2.1)$$

CW_i , the maximum value of contention window of STA i , is initially set as CW_{min} as specified in IEEE 802.11 and depends upon the number of unsuccessful transmission attempts, k , $CW_i = (CW_{min} + 1) \cdot 2^{k-1} - 1$. Every time a transmission fails, e.g. due to collision at the receivers, k and CW_i increment till the maximum value of CW , CW_{max} . When reaching CW_{max} and collision at receivers occurs again, STA i restarts backoff time from the initial value, CW_{min} . The backoff time in transmission reduces the possibility of collision caused by the STAs transmitting messages simultaneously, especially at the higher value of CW_i . Avoidance of collision, however, is at the cost of greater waiting time before transmission.

The STA first transmits a Request-to-Send (RTS) packet to the destination upon occupying the channel. The destination responds to the transmitting STA with a Clear-to-Send (CTS) packet. Then the STA begins to transmit the data message before the destination replies with an acknowledge (ACK) message to confirm that the message from the STA is successfully received. After sending the ACK, the destination forwards the message if the channel is idle; otherwise, the destination keeps listening to the channel until it is idle.

Note that after the STA occupies the channel and exchanges messages with the destination, a Short InterFrame Space (SIFS) is adopted before the response of both transmitter and receiver, as is shown in Figure 2.2. SIFS is shorter than DIFS, which avoids the other STAs in DIFS

from identifying the channel as idle and contending for the channel in the period of the SIFS. SIFS is used for the highest priority transmission and is the shortest time that an STA switches to receive/transmit mode.

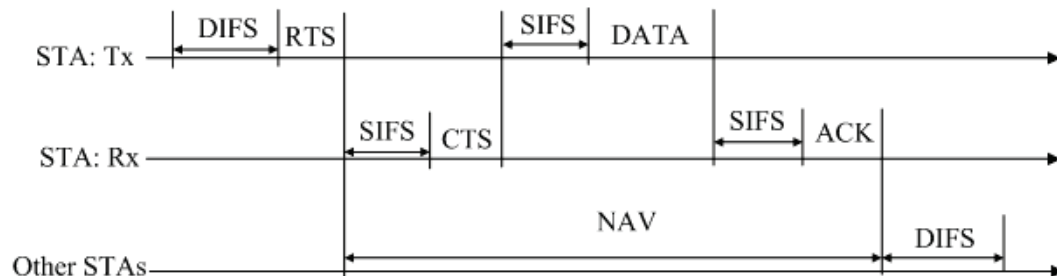


Figure 2.2: DCF access mechanism [1]

In addition, the Network Allocation Vector (NAV) is used in DCF. The MAC layer frame contains the Duration field indicating the time the ongoing transmission of STA will occupy the channel. The Duration field in the MAC layer frame is set as the NAV by other STAs trying to accessing the channel in the network, who then sleep for the indicated time in the MAC layer frame to avoid sensing the channel. This virtual carrier sensing mechanism of NAV limits the power used by STAs to sense the channel. The NAV is updated every time the STAs receive a MAC frame in which the Duration field exceeds the current ending time of NAV; otherwise, the NAV remains the current ending time and continues counting down. When the NAV counts down to zero, the STA starts to sense the channel, checking whether it is idle or not.

2.3 Routing protocols in VANETs

The similarity between MANETs and VANETs enables protocols in MANETs to be applied in VANETs. Yet, performance of these protocols can be affected, due to the features listed in the previous section which distinguish VANETs from MANETs. Reliability and stability are the key factors to be considered in protocol design of VANETs due to their dynamic property and frequent disconnection. For safety applications, which require fast delivery of messages, propagation latency is an important factor that needs to be considered in protocol design. The routing protocols in VANETs can be categorised into several types [8]: broadcast routing, position-based routing (geographic routing), cluster-based routing, geocast routing, and topology-based

routing. Notice that in the current literature, the features and the advantages of different types of protocols are often combined in one protocol to deal with network mobility, e.g. the combination of position-based routing and broadcast routing or a topology-based protocol.

2.3.1 Broadcasting protocols

Flooding broadcast is a simple and straightforward method of message dissemination. In a flooding scheme, every node receiving the message forwards the message. Yet, the problems caused by flooding, e.g. waste of bandwidth and frequent collisions, make it an inefficient method especially in the case of a dense network. Broadcast storm in VANETs is quantified [13], which indicates that in the flooding scheme, with the increase of vehicle density, the transmission performance is significantly affected, in terms of the number of hops, total delay and packet loss ratio.

Selective forwarding schemes are used to improve the performance of the flooding scheme [13]. In weighted p -persistence broadcasting, if a message is received for the first time, the receiver forwards the message with a specific probability p , which is the ratio of the distance between the transmitter and the receiver to the transmission range. That is, the farther receivers to the transmitter forward the message with higher probability. In addition, slotted 1-Persistence broadcasting permits the receiver to forward the message with probability 1 in the pre-assigned time slot. The assigned time slot relates to the one-hop delay, total number of time slots and the distance from the transmitter to the receiver. In slotted p -persistence broadcast, the hybrid scheme, the receivers forward the message in a pre-assigned time slot with a specific probability. Both the assigned time slot and the probability relate to the distance from the transmitter to the receiver. Broadcast redundancy and packet loss ratio are reduced by up to 70% compared to flooding and the propagation latency is still at acceptable levels.

The properties of urban traffic are analysed and compared with the highway scenario [14], and Urban Vehicular Broadcast protocol (UV-Cast) is proposed. Store-Carry-Forward (SCF) scheme is adopted in UV-Cast. Region of interest (ROI) in the highway scenario is usually uni-directional along the road while in an urban scenario ROI is multi-directional. Therefore, the broadcast scheme for the highway needs to be modified from the one applied in the urban case. More than one vehicle is selected as the relay for SCF in the urban case, since one relay may fail to propagate the messages in all directions considering the direction of movement of the relay. A relay for SCF forwards the message more than once to inform all the possible vehicles

in the ROI. Experiments in an urban scenario show excellent performance of UV-Case in terms of reachability and network overhead.

A Border node-Based Routing (BBR) protocol is proposed for a partially connected network [15], e.g. VANETs in a rural area. The border node is defined as the node with minimum common neighbour nodes with the transmitter, which is the furthest node from the transmitter within the transmission range. As is shown in figure 2.3, the common neighbours between vehicle Tx and 1 are vehicle 4 and 5. While for vehicle 2, 3, 4 and 5, the number of common vehicles with vehicle Tx is 3 or more. Therefore, vehicle 1 is the border node. In BBR, the beacon message is sent out by the network layer of the nodes to claim their existence and one-hop neighbour information is collected, since it is assumed that the location information is unavailable for the vehicles. As the transmitter broadcasts a message, the border node of the transmitter forwards the message in a flooding way. Simulation indicates that a high packet delivery ratio can be achieved in a highly partitioned network, e.g. a rural network, by using a limited flooding scheme, e.g. BBR, although flooding schemes cause problems resulting in low delivery ratio in dense networks.

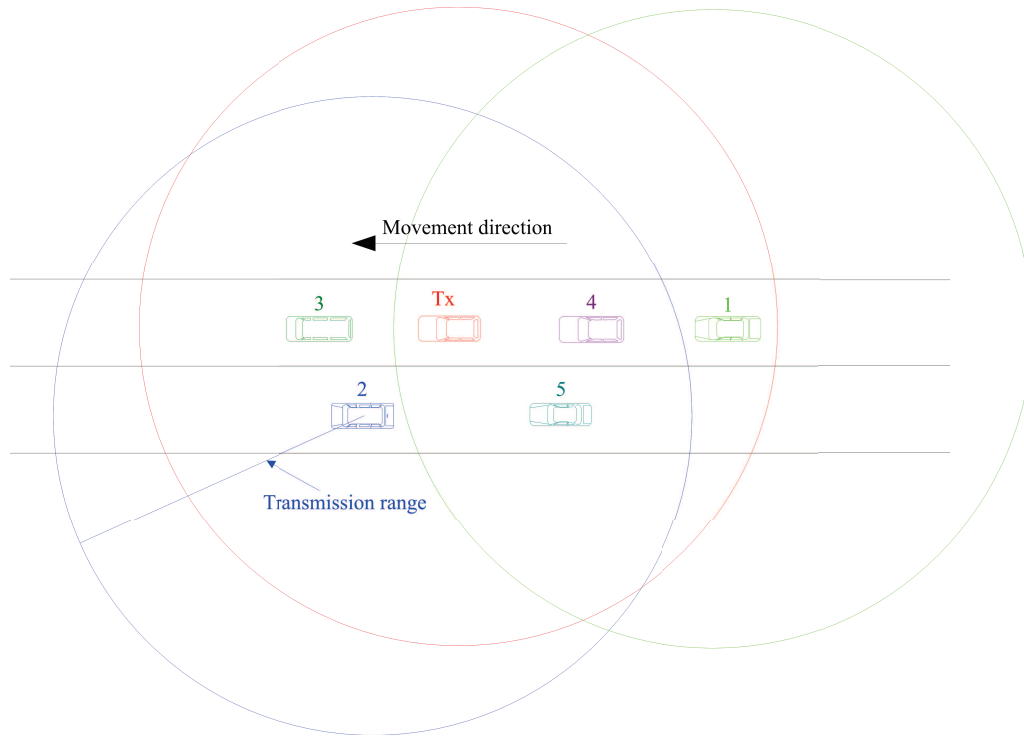


Figure 2.3: *Illustration of border node*

Broadcasting protocols are a simple and straightforward method of message propagation in vehicular environments but the issues, e.g. broadcast storm, can lead to low efficiency of message propagation in dense traffic.

2.3.2 Cluster-based Protocols

In cluster-based protocols, a virtual chain of networks is created for message propagation, unlike the flooding scheme adopted in IEEE 802.11, in which every node is involved in forwarding messages. The vehicles are grouped geographically as clusters. The size of the cluster depends on the radio range of wireless devices adopted in the network. The cluster head (CH) is selected in each cluster and it takes charge of inter-cluster communication. Cluster members communicate directly with members in the same cluster and via CHs with vehicles in other clusters. The stable and reliable communication between CHs affects the system performance.

In a cross layer protocol for alert message propagation in VANETs [16], predefined backbone members (BM) are selected to forward messages prior to the propagation, which is named as DBA-MAC, Dynamic Backbone Assistance MAC. Once a vehicle has not received any messages from nearby BMs for a specific period, it upgrades itself as a BM and broadcasts a beacon to create a BM network. The vehicles receiving a beacon, which then become BM candidates, start a contention to be the next BM. The suitability as a BM is measured by the relative distance between the BM candidates and the BM at the end of the predefined period, the one with the longest distance winning contention with the highest probability. During message propagation, only BMs forward messages from the preceding BM. Once a BM fails to forward a message all the other vehicles start contention to forward the message. A scheme of on-line game message propagation [57, 81] is similar to DBA-MAC [16]. Each time a message is to be transmitted, a beacon is broadcast to start a contention. The suitability of the vehicles is determined by the relative distance, similar to the BM selection scheme [16]. The propagation scheme for online game messages [57, 81] is the basis for the on-demand part and the BM selection part of DBA-MAC [16]. The difference between on-line game message propagation and DBA-MAC lies in the fact that in DBA-MAC it is assumed that every vehicle has a constant radio range and this assumption in the former scheme has been relaxed. And the ratio of relative distance to Tx and the unique radio range of Tx is used to calculate the suitability of candidates.

The Affinity Propagation algorithm is adopted to select CH in a distributed manner periodically [17]. Considering node location and mobility, similarity function between nodes within

mutual radio range is built, which is related to the sum of negative Euclidean distance between two nodes now and in the future. In order to achieve a stable CH link, the proposed protocol is able to group vehicles into clusters which minimise relative mobility between CHs and the distance between CHs and cluster members. To deal with the situation where CHs lose connection, a scheme whereby more than one CH is used to forward messages is proposed [18]. The network formation procedure is divided into two phases, a setup phase and a maintenance phase. In the setup phase a normal node claims to be a CH if it does not receive any messages from nearby CHs. CHs broadcast beacons to create a CH network. In the maintenance phase, a secondary CH (SCH) is selected. A weighted sum of speed difference and location distance between CH and any cluster member can be acquired and the member with the minimum sum is selected as the SCH. If the CH leaves the cluster network, the SCH undertakes message propagation and upgrades itself to the CH of the cluster.

The cluster-based protocols disseminate messages through a CH, which reduces the contention, collision and thus energy consumption of vehicles in message propagation.

2.3.3 Ad hoc (Topology-based) Routing Protocols

Ad hoc routing protocols in MANETs, e.g. Ad hoc On-Demand Vector (AODV) and Dynamic Source Routing (DSR), are also applicable in VANETs. These protocols in MANETs are designed for relatively stable networks and the performance is significantly affected by the dynamic character of VANETs. In the literatures [19–22], it is assumed that the vehicles are equipped with GPS devices which provide the location and speed of the vehicles exactly.

Traffic information is the key factor in the improvement of routing protocols which were originally designed for MANETs, especially AODV. In AODV [19], the source broadcasts a route request (RREQ) before a message is transmitted. A nearby node either responds with a route reply (RREP) if it stores a route to the destination, or it rebroadcasts the RREQ. When the destination receives the RREQ, it replies with a RREP and the RREP is propagated back to the source. The message transmission starts as soon as the RREP is received. If a RREP with a smaller hopcount to the destination is received, the source updates the route and adopts the new route for message propagation. In the event of link failure, the upstream node of the breakage reports to the source, and the source re-initiates finding a route if necessary. DAODV [20] improves AODV by including mobility information in route selection. It is assumed that every vehicle in a network is equipped with Global Positioning System (GPS) and the mobility infor-

mation, i.e. direction and location, is provided by GPS. During route discovery, the direction of candidates needs to be checked. Only candidates moving in the same direction as the source and/or destination are considered to be potential candidates. Furthermore, among the potential candidates, the ones in between the source and the destination are the only ones to respond to the source. If no potential candidate is found between them, all the potential candidates respond to the source to build the route. The model is applicable to the case of travel both in the same and opposite directions.

As well as direction of motion, the speed of nodes can be considered in the phase of route discovery to reduce overhead [21]. The candidates with similar speed travelling in the same direction as the source/previous relay in the route are marked with smaller link weight, the index which indicates the similarity of speed between candidates and source. A maximum number of routes, $number_{bound}$, are defined and only up to $number_{bound}$ candidates with smallest link weight are able to respond to the source/previous relay; therefore, the number of routes and overhead of route discovery is limited. Furthermore, to select a reliable and stable route, the link and route expiration time are estimated. During route discovery, the link time for each pair of adjacent relays is estimated based on the transmission range and relative speed. The route expiration time is the minimum link time of all the relay pairs in the route. The link and route expiration time are stored in the RREP back to the source and the route with longest expiration time is chosen for message broadcast.

To reduce the overhead of route establishment, Prior AODV (PAODV) [22] is proposed by limiting the number of routes and number of candidates for the routes. Before route discovery, an upper bound of the number of routes is set to limit the number of routes as well as the number of candidates responding to the source. Limiting the number of responses minimises the overhead of route discovery. In addition, the source filters candidates spatially. Routes that include the candidates lying within a short distance from the transmitter as intermediate nodes, if selected, are likely to lead to longer routes and result in low efficiency in route discovery and message forwarding. The protocol defines an exclusion region around the transmitter, such that nodes within this region are not selected for routing. Only candidates outside the specific distance, but within the transmission range are able to act as a relay in the route. Combining the two selection schemes, fewer routes are selected and the distance between adjacent relays in the routes are larger on average than the one in AODV and performance in terms of route length and overhead is improved.

2.3.4 Position based protocols

Route map and Global Positioning System (GPS) provide location of vehicles in VANETs. To transmit the message from the source to the destination, location information can be used to find a route from the source to the destination for message propagation. To take account of network mobility of VANETs, the traffic information is often used to predict the location of potential relays for the stability of the route.

Greedy Perimeter Stateless Routing (GPSR) [23] is one of the most famous position-based protocols. It is assumed that the position of every node and the destination in the network is known by others. As a message is generated to be transmitted, the transmitter finds a node closest to the destination to forward the message.

If the transmitter fails to find the greedy path, the packet is forwarded in perimeter mode, in which it traverses along the closer faces of a planar graph of the network in turn, and the greedy forwarding restarts if a node closer to the destination than the current node is found. This procedure ceases when a node closer to the destination is found and the greedy forwarding procedure continues. GPSR was designed for MANETs and in VANETs it has to deal with network mobility. To enable GPSR to be efficient in VANETs, the future location of vehicles can be considered with GPSR [24, 25]. Once a node is about to transmit a message, it estimates the geographic location of each neighbour after a specific time T , based on current velocity, current location and direction of movement. The vehicles outside the communication range after T are excluded from the possible intermediate nodes. Among the remaining nodes, the one closest to the destination implements forwarding the message.

Smart Broadcast (SB) protocol is proposed [26], in which the location of potential intermediate nodes determines the priority of vehicles to forward the message. Before a message is transmitted, a Request-to-send (RTS) packet is broadcast by the transmitter to find the relay nodes. To determine the relay node, all the nodes receiving the RTS start a backoff procedure and the waiting time is related to the distance from the node to the transmitter. The coverage of the transmitter is divided into sectors and each sector shares the same range of backoff time. The nodes with longer distances to the transmitter finish backoff prior to the ones with shorter distances. The winner in this contention procedure responds with a Clear-to-broadcast (CTB) packet to the transmitter before the transmitter starts propagating the message. This procedure repeats until the message arrives at the destination.

Position-based schemes can be merged with other types of protocol, e.g. topology-based AODV, to carry out message propagation. HLAR [27], a hybrid protocol, is proposed, which contains features of location-based routing and AODV. The source broadcasts a route request (RREQ) before a message is transmitted, with a time-to-live (TTL) packet which estimates hop-count to avoid unnecessary flooding in the network. The sequence number of the intermediate node, IP address of the node, and sources information are included in the RREQ. The nearby node responds with a route reply (RREP) if it has a route to the destination, or rebroadcasts the RREQ. As the destination receives the RREQ, it replies with an RREP and the message is propagated back to the source, before the source is able to transmit the message. Considering the dynamics of networks, if the link breaks during message propagation, the nodes of the broken link are permitted to repair the broken part of the route to find the route to the destination, instead of unicasting the breakage information to the source and re-building a new route from the source. The intermediate nodes locally broadcast beacons to neighbouring vehicles which are closer to the destination if such nodes exist or flood a route repair message to inform nearby nodes which are still connected to the destination.

Position-based protocols distinguish vehicles by location and provide the vehicles closer to the destination with priority to forward messages, which improves the efficiency of message propagation.

2.3.5 Geocast protocols

Geocast routing protocols set an ROI which is determined by the location of the message source. Packets, e.g. information on accident and congestion, are propagated to all the vehicles in the ROI. Other types of routing protocols, e.g. position-based protocols, can be combined with geocast routing to achieve efficient propagation of messages in an ROI.

Vehicles travelling in the opposite direction may be used to relay the message through the region of interest [28, 29]. The vehicles moving in the same direction are grouped based on the transmission range [28], and a group head (GH) is selected for each individual group. Once an incident is triggered, the vehicle involved in the incident, as the message source, broadcasts a message to inform other vehicles about the event. If the network condition cannot guarantee that the message is transmitted throughout the region of interest, e.g. the disconnected case, GHs travelling in the opposite direction take charge of forwarding the message. Once a GH receives the message and rebroadcasts it, the source stops periodical broadcast upon sensing the

rebroadcasting. The GH travelling in the opposite direction rebroadcasts the message before it moves out of the region of interest. The adoption of vehicles travelling in the opposite direction provides acceptable levels of delivery ratio and broadcast cost in either dense or sparse traffic.

A cached scheme to geocast routing is introduced [30]. Once a node holding a message loses its connection with others, it stores the message in its cache and waits to establish connection. Nodes in the network periodically broadcast beacons to inform nearby nodes of their existence. If the node with messages to be transmitted again receives a beacon, it starts broadcasting the message. The delivery ratio is improved by the cache scheme. In addition, a location constraint scheme is proposed to keep the route connected. The selected intermediate node, based on greedy routing, is always the closest to the destination. The selection range of the next relay, therefore, is reduced to guarantee network connectivity. That is, vehicles outside the transmission range after a specific interval are excluded from the potential relays. The scheme decreases network load and delivery delay.

Different from the passive reception of traffic information in other protocols, a pull-based geocast protocol is proposed [31]. In this scheme, after setting the destination, the vehicle broadcasts a request for information on congestion and the receivers in between the current location of the vehicle and the destination forward the request to their neighbours as far as the vehicles near the destination. The area from the location of the requester to the destination is defined as the ROI. In addition, the receivers respond to the requester with a congestion index which indicates the local congestion level. With this pull-based approach, the requester is able to obtain the congestion information for the possible routes to the destination and to choose the one with the shortest delay.

2.3.6 VANETs Routing Protocols with Consideration of Height

In practical traffic conditions, the vehicles between Tx and Rx are the main source of the signal attenuation [32, 33]. Intuitively, tall vehicles are better than low vehicles as intermediate nodes. It has been proved by experiments [34] that tall vehicles as intermediate nodes, instead of low vehicles, help to improve the performance of signal propagation in terms of the received signal power, packet delivery ratio and effective communication range. This is because the vehicles as obstacles have a smaller impact on signals from tall vehicles than from lower ones. In the experiments, it is assumed that the vehicles receiving the message know the number of neighbouring vehicles. The farthest low and tall vehicles among the receivers compare the

number of their neighbours, and the one with the most neighbours forwards the message. In the experiments, the ratio of tall vehicles was spread from 0.05 to 0.5. The results indicate that tall vehicles have more neighbours and they forward the message with higher probability. Using tall vehicles as intermediate nodes can be applied to any type of routing protocols in VANETs.

A clustering protocol, Spring Clustering, is improved by considering vehicles' height, which has been named Enhanced Spring Clustering (ESC) [35, 36]. In the ESC, a cluster head is elected using Coulombs law for the stability of a cluster network. The suitability of a candidate, the analogy with the force in Coulombs law, is

$$F_{rel_{ijx}} = k_{ijx} \frac{q_i q_j}{r_{ij}^2}, F_{rel_{ijy}} = k_{ijy} \frac{q_i q_j}{r_{ij}^2} \quad (2.2)$$

where $F_{rel_{ijx}}$ and $F_{rel_{ijy}}$ are the pairwise relative forces between vehicles i and j along the x axis and y axis. The two axes are the movement directions of the vehicles, which are vertical to each other. r_{ij} is the relative distance between vehicles i and j . k_{ijx} and k_{ijy} indicate whether the vehicles are approaching each other ($k_{ijx} > 0$) or departing ($k_{ijx} < 0$), which relates to their relative speed. q_i and q_j are the factors which distinguish tall vehicles from low ones. As vehicle i belongs to the group of tall vehicles (assuming that the vehicles are divided into tall and low vehicles), $q_i = 2$; otherwise, $q_i = 1/2$. For any vehicle, the sum of $F_{rel_{ijx}}$ with all its neighbouring vehicles, F_x and F_y , are $\sum F_{rel_{ijx}}$ and $\sum F_{rel_{ijy}}$, which are the total force of vehicle i . The vehicles broadcast beacon messages periodically, which contain the information of their location, movement direction and speed. The force F_{rel} of each other, therefore, can be exchanged. The candidate with the highest F_{rel} , is equivalent to the situation where the candidate is likely to be a tall vehicle and is at a smaller distance from its neighbours, and is thus best suited to be the cluster head. This method aims to improve the performance regarding the cluster lifetime and the stability of the link between cluster heads. However the mechanism of periodic beacons from all the vehicles could be a source of congestion in the channel, especially in heavy traffic.

2.4 Backoff Analysis: Transmission Probability

The backoff mechanism in IEEE 802.11 is adopted to avoid collision, since stations may try to access idle channels at the same time. Random backoff time is specified, forcing stations to defer the starting time of transmission by various degrees. This mechanism determines the

transmission probability of stations and whether the message can be transmitted in the cases where there is only one winner in channel contention.

The transmission probability of any station in a random time slot is deduced using a Markov chain [37]. It is assumed that there are always messages to be transmitted at any station. If the channel is sensed to be idle and the backoff counter of a station reaches zero, a message will be transmitted by the station. Other stations receiving the message pause the backoff procedure and only restart the backoff whenever the channel is released. It is also assumed that the packet collides with a constant and independent value p_{co} regardless of re-transmission numbers. The backoff process is modelled using a discrete Markov chain,

$$P(i, k | i, k + 1) = 1, k \in (0, W_i - 2), i \in (0, m) \quad (2.3)$$

$$P(0, k | i, 0) = \frac{1-p}{W_0}, k \in (0, W_0 - 1), i \in (0, m) \quad (2.4)$$

$$P(i, k | i - 1, 0) = \frac{p}{W_i}, k \in (0, W_i - 1), i \in (1, m) \quad (2.5)$$

$$P(m, k | m, 0) = \frac{p}{W_m}, k \in (0, W_m - 1) \quad (2.6)$$

where k represents the randomly-selected backoff value and i is the backoff stage, i.e., the retransmission times. Equations 2.3 to 2.6 represent the one-step transition probability of the Markov chain. $P(i_1, k_1 | i_0, k_0)$, for example, is the transition probability from the backoff stage i_0 and backoff counter k_0 to the backoff stage i_1 and backoff counter k_1 . $W_i = 2^i W$. For the first transmission, $W = CW_{min}$. Equation 2.3 reflects the fact that the backoff value is decreased by one at the start of each time slot. Equation 2.4 shows the probability that a new packet is to be transmitted with a backoff value selected from $W_0 - 1$ and 0, after the successful transmission of a previous message. Equation 2.5 shows the fact that after the $(i - 1)$ th unsuccessful transmission, a new backoff value is selected within a greater range, from $W_i - 1$ to 0. Equation 2.6 indicates that if the range of the backoff selection reaches the peak, $CW_{max} - 1$, and the transmission fails again, the re-selected backoff value is still from $CW_{max} - 1$ to 0.

According to the basic relations listed above, the probability τ that a station will transmit in any chosen time slot is

$$\tau = \frac{2(1 - 2p)}{(1 - 2p)(W + 1) + pW(1 - (2p)^m)} \quad (2.7)$$

where p is the probability of collision and W is the minimum CW, CW_{min} . m represents a predefined maximum CW stage which relates to CW_{min} and CW_{max} . The equation shows that the probability that a station will transmit in a randomly-chosen time slot. p is the probability that at least one of the other $N - 1$ stations will transmit in the same time slot as station i . It is

$$p = 1 - (1 - \tau)^{(N-1)} \quad (2.8)$$

For a system, τ and p are unknown parameters and can only be obtained by numerical methods.

The successful transmission probability of an individual station [38] is studied. It is assumed that there are N stations contending for the shared channel. A station successfully transmits messages if it has the smallest backoff value among all the other stations. $v_i(t)$ is defined as the backoff value which is randomly chosen by station i from $[0, win_i(t)]$, where $win_i(t)$ is the contention window size of node i at time instant t . $P_i(t)$ is the probability of the successful transmission of station i at time t .

$$P_i(t) = P(v_i(t) < v_j(t) | j \neq i, j = 1, \dots, N) \quad (2.9)$$

then $P_i(t)$ is above zero if the backoff value which the station i selected is smaller than the others.

For all the stations, the minimum value of $win_i(t)$, $win_{min} = \min(win_i(t), i \in N)$, is a threshold for successful transmission. If the backoff value of station i is greater than win_{min} , the probability of successful transmission $P_i(t)$ is zero.

If i is the sole station, the backoff value is smaller than win_{min} , then $P_i(t) = 1$. Otherwise, if there are r stations with a backoff value smaller than win_{min} , the opportunity for successful transmission for these r stations is equal, which is $\frac{1}{r+1}$.

To get a general expression of $P_i(t)$, the probability that there are r stations with a backoff value smaller than win_{min} has to be calculated among the other $N - 1$ stations, i.e., $P(r)$.

$$P(r) = \sum_{k=1}^{\binom{N-1}{r}} \left(\prod_{m \in r \text{ in } kth} \frac{win_{min}}{win_m - 1} \prod_{v \in \text{rest in } kth} \frac{win_v - win_{min} - 1}{win_v - 1} \right) \quad (2.10)$$

In Equation 2.10 there are two products. The first term, $\prod_{m \in r \text{ in } kth}$, presents the product of the probability of r stations with a smaller backoff value than win_{min} in the kth combination

of stations. The second term, $\prod_{v \in \text{rest in } k\text{th}}$, shows the product of the probability of the other $N - 1 - r$ stations with a greater backoff value than win_{min} in the k th combination of stations.

$$P_i = \frac{win_{min} - 1}{win_i - 1} \sum_{r=0}^{N-1} \frac{1}{r} P(r) \quad (2.11)$$

Equation 2.11 shows the probability that any station will access the channel successfully and transmit. The calculation [38], however, is too complicated to understand and to implement. The probability of successful transmission will be re-deduced in Chapter 4. The expression in Chapter 4 provides a simplified version of the probability of successful transmission and a specialised form for the proposed scheme in this thesis.

2.5 Network Connectivity in Vehicular Networks

As a fundamental property of ad hoc networks, network connectivity is a prerequisite for network functions, e.g. protocol design and system configuration of wireless devices. The dynamics of VANETs make the network connectivity an important factor to consider in protocol design.

According to graph theory [39], the network is connected if and only if any pair of nodes are connected by at least one path. The network is said to be k -connected if and only if there are k independent paths, with no common part of path shared between any pair of nodes. In VANETs, if any two vehicles are connected, the receiver is able to receive the signal from the transmitter successfully.

2.5.1 Inter-vehicle Spacing Distributions

Studies on VANET connectivity are carried out based on the assumption that the location of vehicles follow a Poisson distribution [40–42], that is the location of any vehicle is uniformly random on the road and independent from each other. The expression of probability density function (PDF) of x is given in Equation 2.12

$$f(k, x) = \frac{(\rho_v x) e^{-\rho_v x}}{k!}, k \geq 0 \quad (2.12)$$

where ρ_v is the vehicle density in veh/m, x represents the distance considered, in metre. $\rho_v x$ is the average number of vehicles within the range of x metres. The expression shows the probability that k vehicles occur at the distance interval of x metres.

Poisson distribution of location is equivalent to the situation where the inter-vehicle spacing follows an exponential distribution. The PDF of inter-vehicle spacing is

$$ED(x) = \rho_v e^{-\rho_v x} \quad (2.13)$$

The Poisson and exponential distribution are simple models for location distribution. Yet, the empirical data [43] shows that the statistics of inter-vehicle distribution change with time of day and the exponential distribution is not able to describe the distance between vehicles precisely in all periods except sparse traffic flow [44].

Log-normal distribution is adopted to model the inter-arrival time and inter-vehicle distance, x , of free-flow traffic [44–46], i.e., $X \in \log_e N(\mu, \sigma)$, where μ and σ represent the mean and standard deviation of log-normal distribution. By comparing with practical traffic data, it is shown [44] that log-normal distribution is more accurate than exponential distribution to model heavy flow traffic.

A statistical model more suitable and accurate than exponential distribution distance is described [43, 47]. The condition of real traffic changes with time in one day. For example, the average distance between consecutive vehicles during daytime is much smaller than the one in the midnight. To acquire the statistical property of inter-vehicle distance, 24 CDF (Cumulative Distribution Function) curves of inter-vehicle distance are drawn from the real traffic data of Berkeley Highway Lab with each one matching one hour in a day. The Kolmogorov-Smirnov test (K-S test) is used to approximate the CDF curves to the pre-selected distributions, i.e. exponential distribution and generalised extreme value (GEV) distribution. If the difference between the CDF curves of traffic data and pre-selected distance is above the threshold of the critical level, which presents the level of similarity, the data can be represented by the distribution. The K-S test shows that in the hours with light traffic conditions, e.g. from 1 a.m. to 5 a.m., the exponential distribution is accurate enough to represent the real traffic data, according to the threshold of critical level 95%. In the cases of relatively heavy traffic, i.e. from 7 a.m. to 10 a.m. and from 2 p.m. to 7 p.m., either of the hypothesised distributions is able to approximate the CDF curves. And in other hours with moderate traffic, the data of distance between consec-

utive vehicles can be properly described by GEV distribution. GEV distribution contains type I, II and III extreme value distributions and forms a family of continuous probability distribution. The distribution is the limit distribution of the normalised maxima of an i.i.d. random variables and thus used to approximate the maxima of finite sequences of random variables. To model the traffic flow with log-normal distribution and GEV distribution, the parameters in the distributions need to be adjusted carefully.

2.5.2 Factors Related to the Network Connectivity

Current research shows that the network connectivity in vehicular networks is mainly determined by the following factors: 1) vehicle density; 2) transmission power, or the maximum transmission range (MTR); 3) network mobility; 4) whether roadside units (RS)/infrastructures are involved in the communication; and 5) impact from environments on signal propagation.

2.5.2.1 Vehicle Density and Transmission Range

Intuitively the network connectivity in VANETs rises with the increase of vehicle density and it is supported by experiments [48]. For a specific connection probability, the trend of vehicle density is opposite to the one of MTR, and these two factors are considered together [2, 49]. The analytical model of connection probability for unidirectional traffic is presented [2]. The distance between consecutive vehicles and the transmission range in VANETs determine the network connectivity. The network is connected if and only if consecutive vehicles are always connected, i.e. the distance between any pair of consecutive vehicles is smaller than the transmission range. The CDF of the distance between consecutive vehicles is [2]

$$F_{cv}(x) = \begin{cases} 1 - e^{-\rho_v x} & x \geq 0 \\ 0 & x < 0 \end{cases} \quad (2.14)$$

Therefore, the connection probability for a pair of vehicles with $N - 1$ relays (vehicles) is

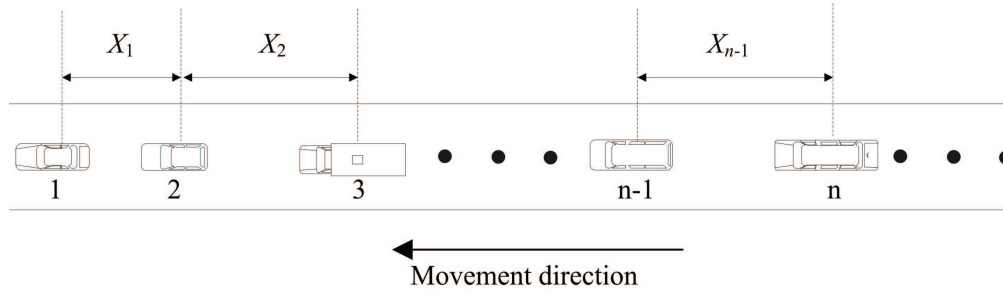


Figure 2.4: Vehicle distribution of one-way scenario [2]

$$\begin{aligned}
 P_c &= Pr(X_1 \leq RR, X_2 \leq RR, \dots, X_{N-1} \leq RR) \\
 &= (1 - e^{-\rho_v \cdot RR})^{N-1}
 \end{aligned} \tag{2.15}$$

where X_1 represents the distance between vehicle 1 and vehicle 2, and so on. RR indicates the Radio Range of the wireless devices. Figure 2.5 presents the change of connection probability with the vehicle density and the transmission range, based on Equation 2.15. The rise of vehicle density and transmission range increases the connection probability as expected, as is shown in figure 2.5.

Minimum Transmission Range (MTR), that is the transmission range which keeps the connection probability above a specified threshold, is

$$d_c = -\frac{1}{\rho_v} \ln \left(1 - P_c^{\frac{1}{(N-1)}} \right) \tag{2.16}$$

By increasing the transmission range, the required connection probability at a specific density can be raised.

The theoretical analysis above only applies to a straight highway scenario, with no intersections. At intersections [49], the traffic flow is disrupted, which results in significant difference in terms of vehicle density at both sides of the intersection point. Therefore, the increase of vehicle density cannot rise connectivity necessarily.

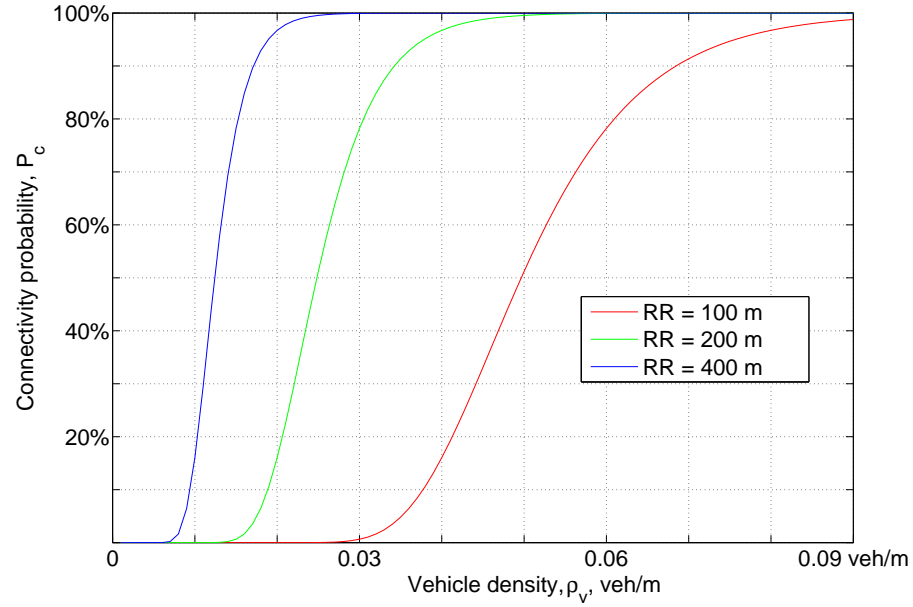


Figure 2.5: *Connectivity probability with the density and the transmission range in one-way case*

2.5.2.2 Network Mobility

As the distinguishing property of VANETs, network mobility affects network connectivity. The metrics to measure network mobility are the mean value and the standard deviation of speed distribution.

The connection probability of VANETs in the highway scenario decreases as the mean and standard deviation of speed increase [50].

The availability of connections for each individual link determines the connectivity of the whole network. Using real traffic data, duration of the link between consecutive relays is analysed in a geometrical view based on the mathematical model of the connection availability [51]. Mathematical models show that in the highway scenario the links between relay nodes moving in the same direction last for a significant amount of time, in the order of tens of seconds. If the vehicles moving in the opposite direction are adopted as relay nodes, the connection time will decrease, since the speed gap of vehicles in the opposite direction results in a shorter time that the vehicles lie within mutual transmission range.

2.5.2.3 Roadside Unit (RSU) / Infrastructure

An RSU can provide drivers with the information about traffic condition, e.g. accidents and traffic jams, and an access point to the Internet. An RSU also facilitates the construction of vehicular networks in a centralised manner.

The RSU is equivalent to a static node with stronger transmission power compared to the mobile nodes in VANETs. The network connectivity is degraded by extending the space between adjacent RSUs [40]. Experiments [52] show that the rise of transmission range of RSUs improves the network connectivity and shortens the disconnection interval in vehicular networks. In the V2X network, the decrease of the vehicle density and the transmission range of vehicles has the same impact on the network connectivity with RSUs and reduces access possibility to RSUs [40, 52].

2.5.2.4 Impact from Environments on Signal Propagation

The network connectivity is also affected by environmental factors, e.g. roadside buildings and vehicles on the road. These factors result in the reflection, diffraction and scattering of the transmitted signal, and signal fading at the receiver.

Road tests [32, 33] show that the signal received is the superposition of multipath signals with various delay and strength, among which the signal from the Line of Sight (LOS) path dominates the signal received. In the LOS component [53, 54], the packet delivery ratio and the Received Signal Strength Indication (RSSI) are both significantly affected by the vehicles blocking the path between transmitter and receiver. Any potential receiver may fail to receive the signal although it is within the transmission range of the transmitter due to the vehicles which block the signal. Experiments were conducted between one pair of vehicles with one vehicle as an obstacle in between of them. The obstacle effect, as well as signal fading by multipath, weakens the network connectivity inevitably by affecting the signal reception in real traffic.

2.6 Conclusion

In this chapter, four topics are covered, i.e., the features of VANETs, a brief introduction of WAVE (IEEE 802.p) for vehicular communication, common types of routing protocols in VANETs, and a summary of the factors related to network connectivity in VANETs.

The routing protocols are categorised into 5 types, position-based, broadcasting, cluster-based, geocast and ad hoc routing. Notice that some of the protocols mix the features and advantages of multiple types to deal with the high mobility of VANETs for better performance. In the coming chapters, an improved protocol is proposed based on DBA-MAC (Dynamic Backbone Assisted MAC) which contains the features of cluster based, position-based and geocast protocols and aims to propagate safety message as fast as possible. The analysis and results demonstrate that the proposed scheme increases the probability that the best candidates become the intermediate nodes and reduces the propagation latency. In the practical case, the vehicles between the transmitter and receiver affect the signal propagation. In Chapter 5, network connectivity is estimated based on diffraction models to present the obstacle effect in real traffic, and the necessity of considering the obstacle effect in performance estimation of protocols in VANETs is also shown.

Chapter 3

Improved Scheme for Intermediate Node Selection in Proactive Routing Protocol

3.1 Introduction

Dynamic Backbone-Assisted MAC (DBA-MAC) [16], a hybrid routing protocol, comprises of a proactive protocol and an on-demand one. DBA-MAC provides better system performance in terms of propagation delay and average number of nodes involved in each transmission than flooding in IEEE 802.11. The performance improvement stems from lack of backoff between consecutive transmissions and long distances between adjacent intermediate nodes. Since the intermediate nodes take charge of forwarding messages, the key factors affecting network performance are the manners of selecting intermediate nodes efficiently and keeping the distance between adjacent intermediate nodes as long as possible. In this chapter, DBA-MAC is analysed to speed up message propagation. Based on the analysis, a novel scheme is proposed to improve the selection efficiency of intermediate nodes and system performance. The proposed scheme can also be applicable to other VANET protocols in which the CW mechanism is adopted as the selection criterion.

To the best of our knowledge, in existing VANET proactive protocols, the propagation performance and network formation are measured separately, i.e. propagation delay and overhead/formation time. The network formation time, however, is an inseparable part of a proactive protocol and has an impact on average delay in the protocols. In this chapter, a novel metric, delay taking into account the effect of formation time (DEFT), is proposed for the proactive protocols, in which propagation delay and network formation time are combined. The value of the proposed metric represents the propagation delay with the impact of network formation time on delay.

This chapter is organised as follows: in section 3.2, a novel metric for proactive routing protocols is proposed with the analysis of the impact of network formation time on message propaga-

tion. In section 3.3, a proactive routing protocol, DBA-MAC, which is the basic of the research in this thesis, is briefly introduced. Section 3.4 presents the analysis of the drawbacks of DBA-MAC which affect the BM selection and system performance, and proposals of the improved schemes. Performance comparison between DBA-MAC and the proposals are presented in section 3.5. Section 3.6 concludes the chapter.

3.2 Proposed Metric for Proactive Routing Protocols

Delay in proactive protocol is at the inevitable cost of network formation. A system with short delay is usually with long formation time. To the best of our knowledge, in current literature the delay metric only comprises of the time from transmission by the message generator to the end of the last re-transmission. Formation time/overhead, as an individual metric, is ignored in the delay. To estimate the propagation delay taking into account the impact of network formation, a novel metric is proposed. The proposed metric contains the propagation delay and the effect of network formation time on delay, and is named DEFT, i.e., Delay taking into account the Effect of Formation Time.

In this metric, both propagation delay and formation time are normalised to the unit distance, i.e., 1 km. Given that the network in proactive protocols, e.g. DBA-MAC, updates periodically and the messages are held by generators in the network formation phase, the network formation time is weighted by the ratio of average time of network formation in unit distance to the period. DEFT is expressed as Equation 3.1,

$$T_{dft} = \alpha T_{ft} + T_{delay} \quad (3.1)$$

where T_{dft} is DEFT, α is the parameter of impact from the network formation to the message propagation. In α , the average formation time in unit distance is normalised by all the messages in the period, given that the messages are randomly distributed in time, since in the phase of network formation the message generators suspend the message to be transmitted. Therefore, $\alpha = T_{ft}/period$, where *period* is the updating period in DBA-MAC. T_{ft} is the average formation time of a 1-km network and T_{delay} represents the average propagation delay of the messages in 1 km.

3.3 A Proactive Routing Protocol: DBA-MAC

In DBA-MAC, vehicles with wireless devices are categorised into 2 groups, i.e., backbone members (BMs) and normal members (NMs). When no network is detected in a specific period, vehicles broadcast beacon messages to form one. Upon establishing a BM network, messages are forwarded by BMs. NMs only act as intermediate nodes when BMs fail to forward messages due to collisions or a BM link breakage. A BM forwards a message as soon as it is received from the BM's last counterpart, with no backoff time. Because there is no backoff time when a BM forwards a message, delay is reduced, compared with flooding scheme.

3.3.1 Network Formation: the BM Selection

If a vehicle receives no beacon message from any neighbouring vehicle in a specific period, i.e., 5 seconds, it broadcasts a beacon message to start a BM formation procedure, claiming itself as a BM. The beacon message contains ID information of the transmitter, the radio range and information from the GPS equipment, including speed, location and direction of movement. Following vehicles within its radio range justify whether they are suitable candidates and only the suitable ones start a contention-based procedure to become the next BM. The CW scheme in IEEE 802.11 is adopted to determine the suitability of candidates and their backoff time. The candidate which finishes backoff first replies to the BM with a candidature message prior to others and the BM unicasts an ACK message to the winning candidate. All the other candidates suspend backoff procedure and listen to the channel if they receive a candidature message. After this handshake step, the newly-selected BM repeats the procedure by starting from broadcasting a beacon to find the next BM and form the BM network.

During network formation, suitable candidates are the ones which keep connected with the BM and never overtake the BM throughout the period. Whether a candidate is a suitable one, therefore, depends on the relative speed and relative distance between the BM and the candidate. Those outside a BM's radio range at the end of a period, predicted from the relative speed and relative distance, are excluded from the suitable candidates, since the breakage of the BM link degrades system performance if such candidates are selected as a BM.

Among the suitable candidates, the suitability for each individual is related to the relative distance, relative speed to the last BM, the period of network and the radio range. The candidate with the highest suitability is defined as the one farthest from the BM at the end of a period.

The BM selection in DBA-MAC aims at selecting the farthest candidate at the end of the period with highest probability and implementing fast propagation.

The backoff time of candidates before responding to the BM relates to the relative distance of the candidate to the BM at the end of the period. The relative distance normalised by the Radio Range (RR) is used to measure the suitability of the candidate. An index which shows the suitability is defined here, the Suitability Index (SI), as Equation 3.2

$$SI_i = \frac{\Delta s_i + \Delta v_i t}{RR} \quad (3.2)$$

where Δs_i is the relative distance between candidate i and the BM at the beginning of the period. Since only candidates following the BM are considered, Δs_i is above zero. Δv_i represents the speed gap between the candidate i and the BM. For candidates approaching the BM, $\Delta v_i < 0$, and so on. t indicates the updating period of a BM network. RR stands for the radio range of the wireless device in a BM. Dividing by the distance at the end of the period by the radio range normalises the result. In this research, it is assumed that GPS provides the data of location and velocity, and the data is accurate to 0.1 metre. Therefore, the accuracy of Δs_i and Δv_i is determined by GPS. The CW of candidate i , CW_i , is rewritten as follows [16]:

$$CW_i = (1 - SI_i) (CW_{max} - CW_{min}) + CW_{min} \quad (3.3)$$

where CW_{max} and CW_{min} are the parameters from the IEEE 802.11 scheme, which are 1023 and 15, respectively. Candidate i randomly selects a value, CW'_i , from 1 to CW_i and starts a countdown from CW'_i . Once the countdown procedure terminates, the candidate broadcasts a candidature message to contend to be the next BM.

The BM replies to the first candidate with an ACK message after receiving the candidature message successfully. Subsequent candidature messages from other candidates are ignored. The winning candidate is assigned a unique ID number which is contained in the ACK message. To reduce the network overhead, all the other candidates in backoff phase abort backoff as receiving the candidature message, and store the ID information of the new BM after receiving the ACK message.

Subnetworks may be created on the same highway simultaneously. In the BM selection phase, if a beacon message is received by a BM from another BM in the subnetwork ahead, the receiver responds with a candidature message after SIFS, without backoff. The subnetworks merge in

this way.

3.3.2 Transmission by BMs

BMs play a major role in message propagation. Once a BM receives a message from its upstream BM, it responds with an ACK message after SIFS and forwards the message without any backoff. An ACK message indicates that the downstream BM has received the message successfully and is ready to forward it. The upstream BM which receives the ACK does not forward the message again. NMs receiving the message from BMs keep listening to the channel without forwarding the message.

If a NM broadcasts a message as the message generator, all the following vehicles which receive the message start a contention procedure to forward the message. If a predefined BM receives the message, it forwards the message with high priority. Note that a risk zone for the safety message is set at 1 km in the protocol. The safety message contains the information about traffic congestion, accidents and other road traffic conditions. The messages are not forwarded by any vehicles if the receivers are out of the risk zone of the message generator.

3.3.3 Transmission by NMs

Note that messages are not always forwarded by BMs. Although in the protocol, the vehicles outside the radio range are excluded from being suitable candidates during the BM selection, the BM network may be broken by the network mobility, e.g. an unexpected change of BM speed. In addition, channel collision at a BM also results in reception failure and no forwarding of the message. In these cases, NMs participate in the contention to forward the message after the BM re-transmits the message. A contention-based scheme similar to the one in the BM selection phase is adopted here. The backoff time of the NMs is determined by the relative distance to the transmitter and the radio range 3.4. The one which finishes backoff prior to others forwards the message as an intermediate node.

$$CW_i = \left(1 - \frac{\Delta s_i}{RR}\right) (CW_{max} - CW_{min}) + CW_{min} \quad (3.4)$$

3.4 Proposed Scheme and Analysis

3.4.1 Discussion of DBA-MAC

During message propagation, predefined intermediate nodes in the route table take charge of message propagation in the proactive protocols. The system performance, e.g., latency, is directly related to the route selection in proactive protocols.

BM's are the nodes that forward the messages in DBA-MAC. In the BM selection, the suitability of a candidate is defined by the distance to the last BM at the end of the network period. The candidate with the highest suitability is the one with the farthest distance to the BM. Any candidates projected to be outside the radio range of the BM's wireless device or overtaking the BM at any time in the period are excluded. The backoff time of a specific candidate, i , is a random value selected from 1 to CW_i . Statistically, the candidate with the highest suitability will win the contention with the highest probability.

3.4.1.1 The Suitability Criterion of DBA-MAC

The suitability criterion is the relative distance between the individual candidate and BM at the end of the period, that is, the longer the distance of the candidate at the end of the period, the greater suitability it has. Yet, this criterion ignores the location at the beginning of the period, which may result in the decrease of the distance between adjacent BMs. For example, in Figure 3.1, three vehicles are suitable candidates to be the next BM. The black vehicle indicates the relative location of the candidate at the beginning of the period and the dashed blue vehicle is the one at the end of the period. According to the criterion, candidate 2 will win the contention with the highest probability. However, the distance from candidate 2 to the BM is not the longest at the beginning of the period, which may degrade the average distance between adjacent BMs and affect the propagation performance.

On the other hand, if using the distance at the beginning as the suitability criterion, the situation may occur that a potential BM is an approaching candidate and gets closer to the previous BM than the others at the end, as does candidate 4 in Figure 3.1, which gets closer to the BM than candidate 2 and 3. Once such a candidate is upgraded to a BM, in the selection phase of its downstream BM, the candidate set is affected by its relatively high speed. A leaving candidate is free from such a problem. If the relative distance of a leaving candidate at the beginning is

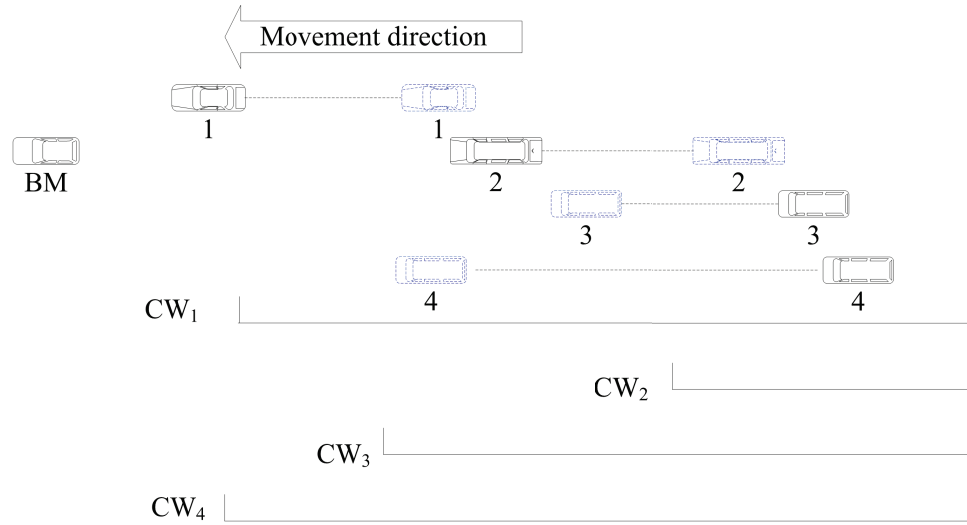


Figure 3.1: Illustration of the ending distance as CW criterion in DBA-MAC

the longest, the distance to the BM only increases throughout the period.

The transfer of criterion changes the SI of leaving candidates; therefore, the SI ranking among all suitable candidates may be changed. Notice that the change may occur only if the traces of the relative distance throughout the period overlap with each other. The following section shows all possible cases which result in the changing of SI ranking, from the final distance (the relative distance at the end of a period) to BM and the initial distance to BM.

Figure 3.2 presents the relative movement of any two candidates with the BM being set as a benchmark. The dashed lines are the trace of the candidates throughout the period. Given the relative speed between the BM and the candidate, the trace indicates the change of the relative distance to the BM in the period. Direction of relative movement is related to the relative speed, i.e., if the candidate is faster than the BM, the relative movement is from the edge of the radio range towards the BM, and vice versa. As is shown in the figure, the relations of the relative distance between any two candidates throughout the period consist of three types, a) no overlap, b) partial overlap and c) fully covered overlap, respectively.

In the case of no overlap, no matter which scheme is adopted and what speed of the candidates are, there is no change of SI ranking. The candidate with longer distance to the BM has higher SI value.

The dash in the table indicates the relative movement direction. For example, B-A in the table

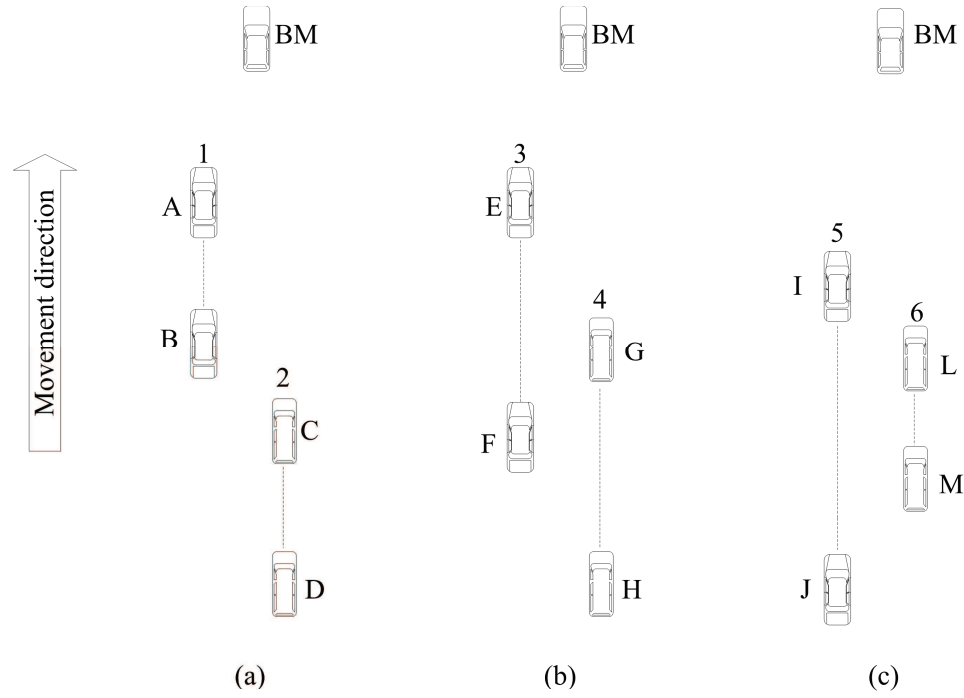


Figure 3.2: Cases of overlap

	SI ranking changed
1:B-A, 2:D-C	N
1:A-B, 2:C-D	N
1:B-A, 2:C-D	N
1:A-B, 2:D-C	N

Table 3.1: Analysis: change of SI ranking in case of no overlap

represents that at the beginning of a period the relative location of the candidate (to BM) is at B and it is at A after a period.

In partial overlap, the cases are grouped into 4 scenarios, which include 1) both approach, 2) both leave, 3) candidate 3 approaches and candidate 4 leaves, and 4) candidate 3 leaves and candidate 4 approaches. In 1), candidate 3 is selected as the BM with higher ranking than candidate 4 in both schemes; in 2), candidate 3 with higher ranking than candidate 4 in both schemes; in 3), candidate 3 has a higher ranking in the scheme of the beginning distance as criterion and a lower ranking in DBA-MAC; in 4), candidate 3 has a higher ranking in DBA-MAC and a lower one in the scheme of the beginning distance as criterion. The following table summarises the change of SI ranking in the partial overlap case.

	SI ranking changed
3:F-E, 4:H-G	N
3:E-F, 4:G-H	N
3:F-E, 4:G-H	Y
3:E-F, 4:H-G	Y

Table 3.2: Analysis: change of SI ranking in case of partial overlap

In full overlap, the cases are grouped into 4 scenarios, i.e., 1) both approach, 2) both leave, 3) candidate 5 approaches and candidate 6 leaves, and 4) candidate 5 leaves and candidate 6 approaches. In 1), candidate 6 has a higher ranking in DBA-MAC and a lower one in the scheme of the beginning distance as selection criterion; in 2), candidate 6 has a higher ranking in the scheme of the beginning distance as selection criterion and a lower one in DBA-MAC; in 3), candidate 6 has a higher ranking in DBA-MAC and a lower one in the scheme of the beginning distance as selection criterion; in 4), candidate 6 has a higher ranking in the proposal and a lower one in the scheme of the beginning distance as selection criterion. The following table summarises the change of SI ranking in the full overlap case.

	SI ranking changed
5:J-I, 6:M-L	Y
5:I-J, 6:L-M	Y
5:J-I, 6:L-M	Y
5:I-J, 6:M-L	Y

Table 3.3: Analysis: change of the SI ranking in case of full overlap

3.4.1.2 Random Selection of CW

A randomly-selected number from 1 to CW_i , which is given in Equation 3.3, determines the backoff time of this candidate. As Figure 3.1 shows, the suitability ranking is $2 > 3 > 1 > 4$, resulting in the upper boundaries: $CW_2 < CW_3 < CW_1 < CW_4$. Candidate 2 will win the contention with the highest probability. Notice that although candidates 1, 3 and 4 are weaker in suitability they also have an opportunity to win the contention. The randomness of CW selection in IEEE 802.11 is designed to avoid collision among competitors. In DBA-MAC, the randomness makes it possible that a candidate with weak suitability becomes the next BM. This reduces the average distance between adjacent BMs and has an impact on system performance.

3.4.2 Proposed Schemes Based on the Analysis

To deal with the issues listed above, schemes to improve the BM selection are proposed, i.e. the CW constraint scheme and the change of suitability criterion.

3.4.2.1 Constraint of CW Selection

To deal with randomness of CW selection and better reflect the candidate suitability, the CW Constraint scheme (CWC) is proposed in the BM selection. CWC is similar to the limited CW selection scheme [55, 56], in which the lower boundary of CW selection is related to the retransmission times. For example, if a station attempts to transmit the message for the i th time, the length of CW selection is $32i$. That is, the selection range of CW spreads from $CW - 32i + 1$ to CW . This method is designed to reduce collisions, yet not suitable to distinguish candidate suitability. This is because the stations with greater retransmission times have a greater range of CW selection. Greater range may lead to greater overlap of CW range with other stations. Stations with greater retransmission may access to the channel prior to the stations with smaller retransmission times. CWC aims to select the candidate of the highest suitability with highest probability. CWC sets an interval for CW selection from the upper boundary CW_i to the lower boundary $CW_i - L + 1$, confining the selection range of all the candidates. The range of CW selection, L , is set to be a number smaller than CW_{min} , the minimum CW of all the candidates. As is shown in Figure 3.3, candidate 3 is the most suitable, so the backoff time for candidate 3 is from CW_3 to $CW_3 - L + 1$. The backoff time of the candidates with weak suitability is greater than the one of CW_3 ; therefore, candidate 3 responds to BM prior to others and will be

the next BM. The suitability of candidate 3 is protected by limiting the backoff time of other candidates with weaker suitability, i.e., 1 and 2. In this way, only if the gap between the upper boundary of two adjacent candidates is great enough, i.e. greater than L , does the candidate with greater suitability terminate backoff prior to the weaker ones. A detailed analysis, with a mathematical model, will be presented in the next chapter.

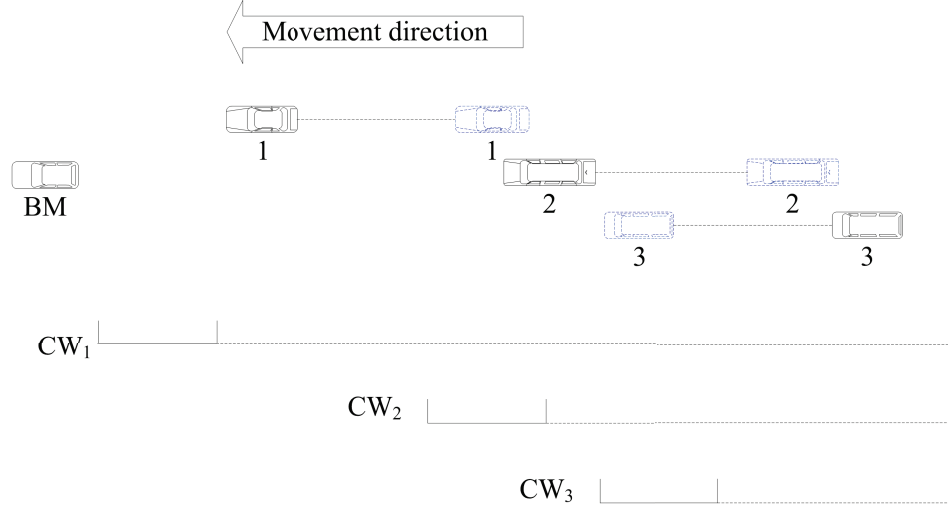


Figure 3.3: *Illustration of criterion in CWC*

3.4.3 Extension of CW Constraint Scheme

A fast delivery scheme for online games in VANETs is presented [57]. The game-event message is propagated among the players in the vehicles in an on-demand manner. To reduce the hop of message propagation, the farther candidates have higher priority to forward the message by the adoption of CW mechanism in IEEE 802.11. The suitability of a candidate to forward a message is measured as Equation 3.5

$$\text{Suitability} = \left\lfloor \frac{RR_i - Dist_i}{RR_i} (CW_{max} - CW_{min}) + CW_{min} \right\rfloor \quad (3.5)$$

where RR_i is the radio range of the wireless devices on vehicle i which transmits the message and $Dist_i$ represents the distance from the current candidate to vehicle i . Note that the radio range is not fixed to a constant value and it is carried by the game message [57]. A random value between 1 and CW is selected to determine the backoff time of the candidate. In addition, the work of game message propagation [57] is extended [58] to more generic applications,

e.g. safety message and road service information propagation. The CW mechanism and Equation 3.5 is also adopted to indicate the suitability of the candidates to forward the messages.

Note that in the scheme for game message propagation [57, 58] the same criterion of candidate suitability is adopted as DBA-MAC. Therefore, the CWC proposed in the thesis is applicable to increase the probability that the candidates with the highest suitability become the relays. The CWC scheme is able to be adopted for the schemes in which CW mechanism is used to distinguish candidates for different priority.

3.4.3.1 Minimum Distance throughout Period as the Suitability Criterion

From the discussion, we see that the maximum distance of a candidate to the BM throughout the period is not always a good metric to determine the suitability. Specifically, the relative distance of the approaching candidates at the beginning and that of the leaving candidates at the end of the period are not the key factors for a long distance of adjacent BMs in the BM selection, due to the speed distribution. In contrast, the minimum distance throughout the period is related to the range of the next BM candidates. To make the distance between adjacent BMs as long as possible, the minimum values of the relative distances of all the candidates can be used as the suitability criterion. The reason to consider minimum values of the relative distance is that the criterion in DBA-MAC aims to get the distance of one hop as long as possible, yet the performance is determined by the average distance of all hops. A novel criterion of suitability is proposed here. The maximum value among the Minimum Distance of all the candidates to the BM throughout the period is adopted as criterion to measure the suitability. The proposal is named as MDC, short for Minimum Distance as Criterion. Different from the SI in Equation 3.2, the SI in the MDC is as Equation 3.6

$$SI_i = \frac{\min(\Delta s_i, \Delta s_i + \Delta v_i t)}{RR} \quad (3.6)$$

The above equation shows that the minimum distance of a candidate determines the suitability as a BM. That is, the initial distance to the BM of a leaving candidate in the period determines its suitability and so does the ending distance of approaching candidates. As candidates which are outside the radio range and overtake the BM are excluded from being suitable candidates, SI_i is a value from 0 to 1. The candidate with the highest value is the best.

Notice that the change of criterion leads to the change of SI value of leaving candidates. This is

because the relative distance of a leaving candidate to the BM is the minimum at the beginning of the period.

Regarding SI ranking, the comparison of ranking change in DBA-MAC and the MDC occurs in some cases. The illustration of vehicles' location is shown in Figure 3.2. For the vehicles without overlap, there is no change of SI ranking. The cases with overlap are listed here.

Partial overlap: in the case of both approaching, candidate 3 is selected as a BM with higher ranking than candidate 4 in both schemes; in the case of both leaving, candidate 3 with higher ranking than candidate 4 in both schemes; in the case of candidate 3 approaching and candidate 4 leaving, candidate 3 has a higher ranking in the MDC and a lower ranking in DBA-MAC; in the case of candidate 3 leaving and candidate 4 approaching, candidate 3 has a higher ranking in both schemes. The following table summarises the change of SI ranking in partial overlap cases.

	SI ranking changed
3:F-E, 4:H-G	N
3:E-F, 4:G-H	N
3:F-E, 4:G-H	Y
3:E-F, 4:H-G	N

Table 3.4: Analysis: change of SI ranking in case of partial overlap

Full overlap: in the case of both approaching, candidate 6 has a higher SI ranking than candidate 5 in both schemes; in the case of both leaving, candidate 6 has a higher ranking in the MDC and candidate 5 has a higher ranking in DBA-MAC; in the case of candidate 5 approaching and candidate 6 leaving, candidate 6 has a higher ranking in both schemes; in the case of candidate 5 leaving and candidate 6 approaching, candidate 6 has a higher ranking in the MDC and candidate 3 has a higher ranking in DBA-MAC. The following table summarises the change of the SI ranking in full overlap cases.

	SI ranking changed
5:J-I, 6:M-L	N
5:I-J, 6:L-M	Y
5:J-I, 6:L-M	N
5:I-J, 6:M-L	Y

Table 3.5: Analysis: change of SI ranking in case of full overlap

For candidates with weak suitability, the change of SI ranking has little impact on the winning probability. For those with the highest suitability and a tiny difference between their SIs, the change of the SI ranking affects their winning probability, especially where the CWC is adopted. We see from the above comparison that a difference of the SI ranking caused by the MDC occurs in 3 cases out of 12, thus the change of the SI ranking by the change of the suitability criterion is not a frequent event in the BM selection. In addition, even if the MDC changes the ranking, the suitability of the candidates involved in the change of SI ranking is unlikely to cause a huge difference in the average distance between adjacent BMs. Simulation results and more analysis of the CWC with mathematical models are presented in Chapter 4.

3.5 Performance and Analysis in DBA-MAC and CWCMD

This section presents the performance comparison between DBA-MAC and the CWCMD. The impact on performance from the rate of safety messages, the rate of the background messages and the vehicle density are presented.

3.5.1 Methodology

To verify that the CWCMD provides faster propagation than DBA-MAC, extensive simulations are conducted.

Event driven programming is carried out in the MATLAB environment, focusing on the MAC layer. Network Simulator 2, as a widely-used tool in VANETs research, is not adopted, since it adds complexity to the simulation and cannot present the results by layer.

In event-driven programming, every individual action on the MAC layer and the routing layer is implemented. For example, once a message generator broadcasts a message (implemented by command Tx_message), a series of actions of the vehicles within the transmission range is triggered, based on various conditions of the vehicles. If the channel is idle and the vehicle keeps listening to the channel, an action of message reception (Rx_message) is triggered. If the vehicle is receiving a message from the other transmitter, a collision occurs (collision_by_safety_message). Nothing is triggered if the potential receiver is transmitting a message.

In the implementation of event-driven programming, an event list is set as a stack to store all

the events. An event is generated with the time instance of its occurrence and is inserted into the event list. The events in the event list are arranged and executed in chronological order. An event is only triggered by the completion of all the events ahead. If all the events are implemented and none remains, the simulation finishes.

Time instant	Event	The vehicle(s) executing the event
...
3.6	Mobility update	all
3.579	end back off	12
3.5	Message generated	57
...

Table 3.6: *Illustration of the event list*

As is shown in Table 3.6, the 1st column of the event list shows the time instant of the event's occurrence. The 2nd column is the name of the event and the 3rd column indicates the index of the vehicle which executes the command.

A command is inserted into the event list as above chronologically. For example, node 12 finishes the back off procedure at time instant 3.579s. Therefore, the event *end back off* by node 12 is inserted and listed before the event *mobility update* at 3.6s. The event is triggered only if the events ahead of it are all executed. Only after the events *end back off* by node 12 at 3.579 and all the other events before time instant 3.6s are finished, the event *mobility update* is triggered.

Safety messages are generated by all the vehicles equally throughout the entire period. The messages can be generated at any time during the period. In the simulation, the safety message rate and the total number of vehicles determine the number of messages. Each message is allocated to a randomly selected vehicle and time instance. The procedure of message generation and time allocation is completed before the period starts, and the corresponding events are executed according to the time order.

The generation of background messages is the same as that of safety messages. It is also determined by the message rate and the vehicle numbers.

The mobility of the vehicular network is independent of the network formation and message propagation. The vehicles are running on a ring-shaped road model which is of 8-km length, with the starting and ending points overlapping. All the vehicles are randomly allocated a

location and a lane on the road in turn until all the vehicles are on the road. Once the location of a vehicle is fixed on the ring-shaped road model, the range of its forward and backward security distance is unavailable for other vehicles to be placed on the model. The process of position allocation restarts only if the road is fully occupied by the vehicles and the corresponding security distances with no space available for the remaining vehicles.

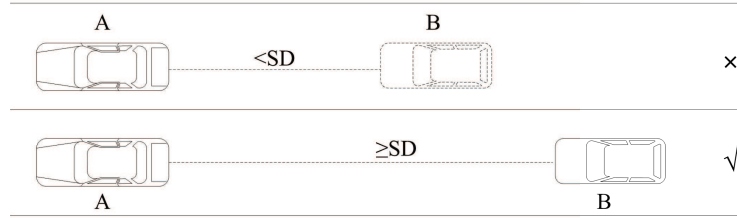


Figure 3.4: *Illustration of security distance*

Figure 3.4 shows that once a vehicle is placed in the security distance of another one, it has to choose the location randomly again until it is out of the security distance of the other one.

The velocity of vehicles is a value randomly selected from the truncated normal distribution. In the initial stage, the speeds of the vehicles are independent of each other. Refer to Section 3.5.2 System Configuration for the parameters of the distribution.

The mobility model, which is free from the impact of communication runs discretely with a time step of 0.1 seconds from the very beginning of each period and the mobility update commands are pushed into the event list before the message propagation. At each step, the vehicles detect the relative distance to the vehicle that is ahead in the same lane. If the distance to the vehicle ahead is smaller than the security distance, the following vehicle decelerates to the lowest speed bounded by the speed distribution in one second to avoid collision.

If the relative distance is not smaller than the security distance, the following vehicles choose to accelerate, decelerate or remain at their current speed with equal probability. Each vehicle has an equal chance of changing speed in this case throughout a given period. As a vehicle is changing speed, the target is to change by a standard deviation of the speed distribution during an entire period. Once the speed reaches the boundary of speed distribution, acceleration stops and the vehicle keeps moving with the boundary speed.

In the simulation, the location of the vehicles at the next time step is predicted based on the current speed and location. The procedure is repeated at every time step until the end of the

period. Overtaking is not considered in this model, since the period of 5 seconds is inadequate for the vehicles to complete the actions of lane changing and overtaking.

A Monte Carlo simulation is conducted to obtain the statistical results. In iteration, since the BM network updates during every period, one entire period of network formation and message propagation is simulated. The network formation starts at the beginning of each period, from the vehicle closest to the edge of the ring-shaped road model along the opposite direction of movement. Propagation delay and other information, e.g. the transmission times of each individual message, are stored in every iteration. To acquire the statistical results, the iteration number is set to 200 in the simulation.

The simulation randomness is guaranteed by the command *RandStream* in MATLAB. The starting moment of the simulation is used as the seed to generate a random stream. Since the starting moment in each simulation is unique, the generated random stream is unique as well as the results.

To get an unbiased result, i.e., delay, the definition of unbiased estimation of standard deviation is used to get the standard deviation of delay. In calculation, $t = \sqrt{\frac{1}{n-1} (\sum (t' - \hat{t})^2)}$, where t' is the simulation result of the propagation delay, \hat{t} represents the average delay and n is the total sample number.

3.5.2 System Configurations

In the simulation, it is assumed that the vehicles are located on a one-way ring-shaped road, on which the starting point and ending point overlap. The location of the vehicles follows a Poisson distribution, except that the distance of adjacent vehicles is equal to or greater than a security distance, which is related to the speed distribution of the vehicles. The vehicle speed follows a truncated normal distribution. For example, the possible speed at a density of 100 veh per km is from $64-6=58$ mph to $64+6=70$ mph. In the mobility model, no overtaking is considered. The actions of overtaking contain the lane changing and overtaking the vehicle ahead from the other lane, which are usually unable to be completed in one period, given the speed distribution and the security distance. The period follows the configuration in DBA-MAC, the selection of which incorporates the consideration of network stability after establishing the network and amount of overhead during network formation. The configuration is listed in Table 3.7 [51]

In the simulation, there are two types of message, i.e., safety messages and background mes-

Vehicle density (veh/km)	100	60, 20
Speed: mean	24 mph	64 mph
Speed: standard deviation	5 mph	6 mph
Speed: range	24 ± 5 mph	64 ± 6 mph
Security distance	25 m	50 m

Table 3.7: Configuration: traffic and mobility model

sages. Safety messages contain information on congestion, traffic accidents and messages about the safety of traffic and drivers. Background messages are the ones which are not safety messages, e.g., information about road service or entertainment messages, and so on. During propagation, if safety messages and background messages are waiting to be transmitted by a vehicle at the same time, it is the safety message that is first transmitted to guarantee its priority. The remaining parameters are listed in Table 3.8 [6, 16]. The message rate is the average number of message a vehicle transmits in each second. For example, message rate 0.2 means that each vehicle transmits 0.2 messages per second on average. It can also be understood as 20% of all the vehicles transmit one message each second.

Radio range	240 m
Length: highway	8 km
Cover range: safety message	1 km
Transmission bit rate R_b	6 Mbps
Length: candidature message L_{candi}	40 bits
Length: ACK message L_{ACK}	40 bits
Length: safety message $L_{sm sg}$	100 bits
Length: background message $L_{bgm sg}$	500 bits
CW_{max}	1023
CW_{min}	15
$DIFS$	$58 \mu s$
$SIFS$	$32 \mu s$
Rate:safety message	0.05, 0.2, 0.5
Rate: background message	0, 1, 2, 4
Updating period	5 seconds
Length of CW selection L	4

Table 3.8: Configuration: system

3.5.3 Simulation Results and Performance Analysis

3.5.3.1 Advantage of DBA-MAC

A comparison between DBA-MAC and the flooding scheme in IEEE 802.11 is presented here. The metrics to estimate the performance are the propagation delay from the safety message generation to reception at the edge of the 1-km risk zone and average number of transmission for each message. The vehicle density is 60 vehicles per km. The rate of safety message generation is 0.2, i.e. 0.2 messages are generated by each vehicle per second on average. The propagation direction of the message is opposite to the movement direction. Figure 3.5 presents the performance comparison between DBA-MAC and flooding in terms of propagation delay.

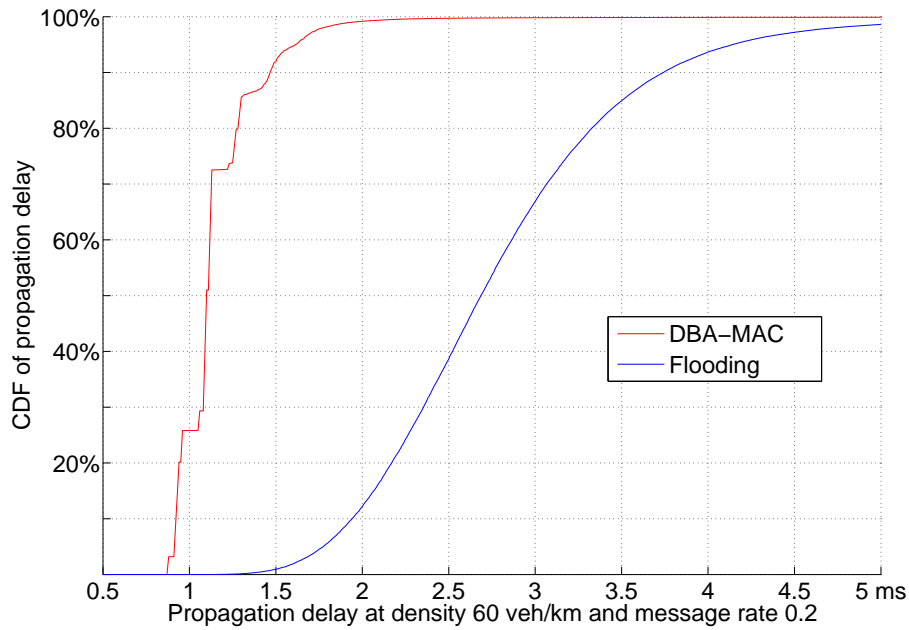


Figure 3.5: The CDF of propagation delay in both DBA-MAC and flooding at a density of 60 veh per km and alert rate being 0.2

	DBA-MAC	Flooding
Aver. number of transmissions	6.05 ± 0.84	9.59 ± 2.29
Aver. delay /ms	1.162 ± 0.542	2.793 ± 0.775

Table 3.9: Average number of transmissions and propagation delay at a density of 60 veh per km rate of safety message 0.2

Figure 3.5 and table 3.9 show that the messages in DBA-MAC are propagated in a shorter delay than in the flooding scheme. In the flooding scheme, the vehicles which receive the message forward it after DIFS and a random backoff time. The backoff time is related to the number of previous transmissions of the message, instead of the relative distance and relative speed of the vehicles. If the message is propagated by the previous intermediate node as the n th time, the maximum CW for candidate i , CW_i , is $2^{2+n} - 1$, $n = 1, 2, \dots, 8$. The vehicles receiving the message forward it with equal opportunity.

Furthermore, in the flooding scheme each time a message is transmitted all the following vehicles within the radio range participate in the contention to forward the message, which reduces the efficiency of channel usage and channel capacity. Based on the configuration of the simulation approximately 14 to 15 vehicles on average join the contention to forward the message. In DBA-MAC, BMs are the only vehicles active for message propagation in the network except when a BM link fails to forward the message.

Due to the usage of BMs in DBA-MAC, the delay of most messages in DBA-MAC is less than 2 ms. In the flooding scheme, the propagation delay varies from 1.5 ms to more than 5 ms. The backoff time before each forwarding and greater number of transmissions are the source of the longer delay in flooding.

Table 3.9 presents the average number of transmissions of a safety message, which includes the broadcast by the message generator. The number of transmissions in the flooding scheme is greater than DBA-MAC and the range varies over a wider range, which is caused by the uniform selection of candidates within the radio range. In DBA-MAC, the candidate with the highest suitability becomes the BM with the highest probability and this accounts for the reduction in average number of transmissions. Note that the average number of transmissions is different from the number of BMs in the risk zone. The average number of transmissions includes transmissions and re-transmissions due to link breakage and collision.

Figure 3.5 shows that the CDF of flooding is more like a continuous curve instead of discrete results, although the results are discrete. This is because flooding delay is spread from 1.5ms to more than 5ms. The randomness of 1) location of intermediate nodes and 2) transmission number for each message in flooding makes delay in flooding more varied than in a predefined BM network, which leads to a visually smooth 'curve' in the CDF.

3.5.3.2 Comparison between the MDC, the CWC and DBA-MAC

In this section, the performance in terms of delay are presented in four schemes, i.e., DBA-MAC, DBA-MAC with MDC (MDC for simplicity), DBA-MAC with the CWC (CWC for simplicity) and DBA-MAC with the CWC and the MDC (the CWCMD). The simulation was conducted at a density of 60 vehicles per km with message rate being 0.05.

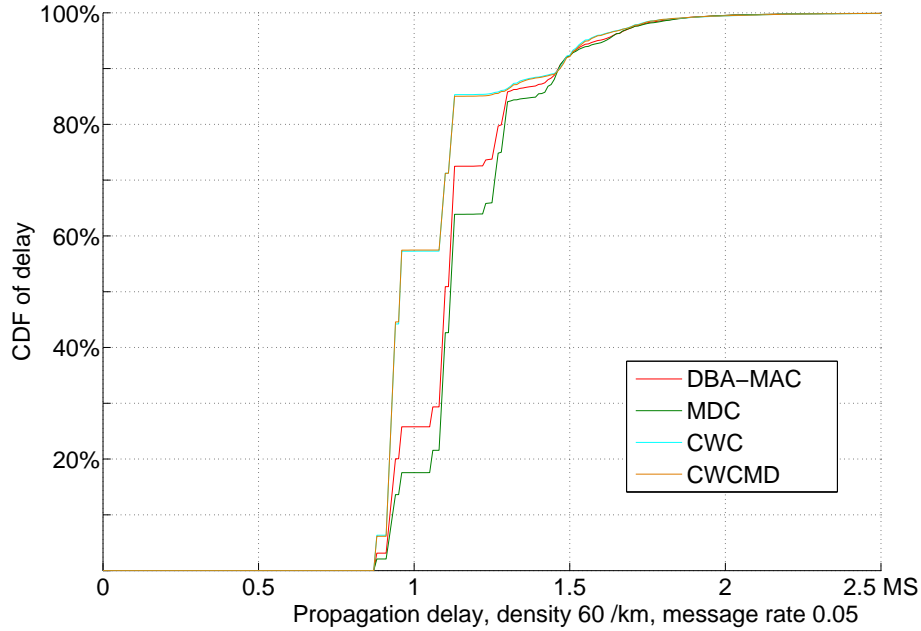


Figure 3.6: The CDF of propagation delay in DBA-MAC, the MDC, the CWC and the CWCMD

Results in Figure 3.6 and table 3.10 show that only if the CWC is adopted, is performance improved, compared with DBA-MAC. The CWC improves the winning probability of candidates with the highest suitability, which is the root of performance improvement. In DBA-MAC, the candidates with the highest suitability finish backoff prior to other candidates with higher probability. In the CWC, the length of backoff time is linear with CW, and the candidate with the highest suitability always finishes backoff prior to the others, which guarantees that the candidate with the highest suitability upgrades to be a BM.

The MDC, however, only manages to improve performance when it is used with the CWC. In the condition that the MDC is combined with the CWC, the candidate with the highest suitability is changed only if the overlap of the relative distance to the BM throughout the period occurs between two or more candidates with the highest suitability, as analysed above. The case

of overlap occurs occasionally, which accounts for the slight improvement of performance.

	DBA-MAC	MDC	CWC	CWCMD
delay	1.144 ± 0.280	1.182 ± 0.372	1.071 ± 0.367	1.070 ± 0.360

Table 3.10: Average delay of DBA-MAC, MDC, CWC and CWCMD at a density of 60

Where the MDC is solely used with DBA-MAC, performance gets worse. Considering the ending distance in the period as the criterion in DBA-MAC, the CW of vehicles with smaller speed than the BM is changed by the MDC. In other words, the MDC only affects the candidates which are leaving the BM and the CWs of approaching candidates are not changed by the MDC. The MDC raises the CW of leaving candidates and the winning probability of all candidates is affected. The MDC leads to the situation where half of the CWs (of the leaving vehicles) become greater than in DBA-MAC and the vehicles with greater CW spread evenly from 0 to the radio range. The equivalent effect is that vehicles with strong suitability tend to be fewer than in DBA-MAC and vehicles with weak suitability increase in number. This effect results in an increase in the possibility of candidates with weaker suitability winning in the BM contention and the performance of the distance between adjacent BMs and propagation delay are both weakened. The overlap of the relative distance among the best candidates occurs occasionally and makes little impact on the performance.

Results show that the CWC makes the major contribution to performance improvement. In the following work, the CWC and the MDC are combined to conduct the simulation and comparison, given the name CWCMD (CW Constraint and Minimum Distance as criterion).

3.5.3.3 Impact of Rate of Safety Message and Background Message on the Performance of DBA-MAC and CWCMD

Message rate	CWCMD	DBA-MAC
0.5	1.114 ± 0.765	1.196 ± 0.858
0.2	1.087 ± 0.565	1.162 ± 0.542
0.05	1.070 ± 0.360	1.144 ± 0.280

Table 3.11: Average delay of DBA-MAC and CWCMD at a density of 60

Figure 3.7 and table 3.11 show that in both DBA-MAC and the CWCMD, the rate of safety

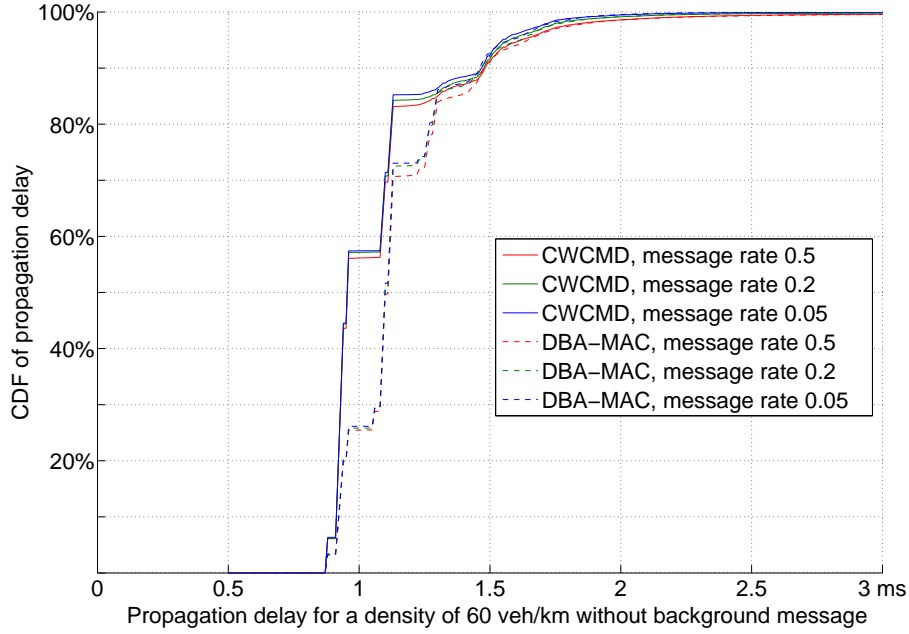


Figure 3.7: The CDF of propagation delay in both schemes at a density of 60 veh per km and changing rate of safety message

messages has little impact on message delay. The CDF curves show that the delay is in the order of *ms*. The interval in which a safety message occupies the channel (order of *ms*) is far less than the network period (5s). Since the messages are distributed equally in time, the impact from other safety messages is insignificant. Besides, once the channel is occupied, only the local channel within the radio range of the transmitter is busy. Channels outside the radio range are free from the impact of the safety message.

It is also noted that flat parts occur in the CDF figure. The horizontal axis of the figure is propagation delay. The flat parts in the CDF indicate that the delay of no message is in the range defined by the values at the both ends of the flat parts. In both DBA-MAC and the CWCMD, the message propagation is among BMs. Due to the propagation scheme adopted in DBA-MAC and the CWCMD, no backoff is introduced during message propagation among BMs. The delay can be estimated, by the transmission times of BMs and backoff time before transmission by the generator. Since the propagation time by each BM is a constant, which is related to the message rate and message length, the delay of messages propagated by the same number of BMs form a group of delay and the delay of no message is in the gap between

different groups. This accounts for the flat parts in the CDF. More details are as follows.

Assuming the message is forwarded by n BMs, the delay T_{delay} is

$$T_{delay} = n(SIFS + T_{ACK} + T_{tx}) + (T_{pre} + T_{tx}) \quad (3.7)$$

$$T_{ACK} = \frac{L_{ACK}}{R_b} \quad (3.8)$$

$$T_{tx} = \frac{L_{msg}}{R_b} \quad (3.9)$$

$$T_{pre} = DIFS + T'_{backoff} \quad (3.10)$$

where T_{ACK} and T_{tx} are the transmission time of an ACK and a safety message. L_{ACK} and L_{msg} define the length of the ACK and the safety message. $DIFS$ and $SIFS$ are DCF Interframe Space duration and Short InterFrame Space duration defined in IEEE 802.11. T_{pre} is the waiting time of the message generator before broadcasting the message. $T'_{backoff}$ shows the backoff time of the message generator if the channel is busy when the message is to be broadcast. The value of n is related to the message's coverage range, the maximum radio range and distance distribution of adjacent BMs. In the condition that the coverage range is 1 km and the radio range is 240 m, the minimum n is 4, which means once the safety message is broadcast by the message generator at least 4 BM transmissions are required. The complete delay by a BM contains a SIFS period, a time period to transmit the ACK message and a time period to transmit a safety message. The time to transmit an ACK message and a safety message depends on the length of the messages and the bitrate, as is shown in Equation 3.8 and 3.9. The delay incurred by the message generator is calculated as the second part of Equation 3.7, which includes a $DIFS$ period after generating a message and a random waiting time before broadcasting.

Also from Figure 3.7, we see that in the same condition, e.g. the same density and the same rate of safety messages, the performance of DBA-MAC is outperformed by the CWCMD, in which more messages are transmitted over the coverage range in a short delay. This results from the shorter re-transmission times and longer distance between adjacent BMs as indicated in table 3.12 and 3.13. In the CWCMD, a message is forwarded fewer times than the one in DBA-MAC on average which is caused by the longer distance between adjacent BMs in the CWCMD.

BM s are selected along the road and due to the stripe-like shape of the road the BM network is

Message rate	CWCMD	DBA-MAC
0.5	5.57 ± 0.76	6.06 ± 0.85
0.2	5.56 ± 0.75	6.05 ± 0.84
0.05	5.55 ± 0.74	6.04 ± 0.84

Table 3.12: Average re-transmission times of DBA-MAC and CWCMD at a density of 60

	CWCMD	DBA-MAC
Aver. distance of adjacent BMs	222.97 ± 12.23	180.21 ± 58.48

Table 3.13: Average distance between adjacent BMs of DBA-MAC and the CWCMD at a density of 60

a chain along the road. Therefore the longer distance among adjacent BMs indicates a smaller number of hops in unit distance. This accounts for the increase of average distance between adjacent BMs leads to a smaller hop number and further smaller average delay.

The following data present the change of performance by each individual scheme.

	CWC	MDC
Aver. distance of adjacent BMs	222.73 ± 12.56	176.43 ± 60.01

Table 3.14: Aver. distance between adjacent BMs by two parts of CWCMD at a density of 60

The results in table 3.14 show that the CWC is the predominant source of performance improvement. The CW scheme adopted in DBA-MAC provides the candidate of the highest suitability with the highest probability of becoming the BM. The candidates of weaker suitability, however, are able to win the contention as well with lower probability. While in the CWCMD, due to the CWC, the candidate of the highest suitability finishes backoff prior to the candidates of weaker suitability and becomes BM, unless the upstream BM fails to receive the message from the candidate of the highest suitability. The chances of the candidates of weaker suitability becoming BMs are reduced, at whatever density. Therefore, the average distance between adjacent BMs is increased in the CWCMD.

Figure 3.8, table 3.15 and 3.16 show how the vehicle density affects system performance. At low density, the location of winners of the BM selection are spread more sparsely and unevenly than at higher density. This means the possibility of a shorter distance at low density is higher

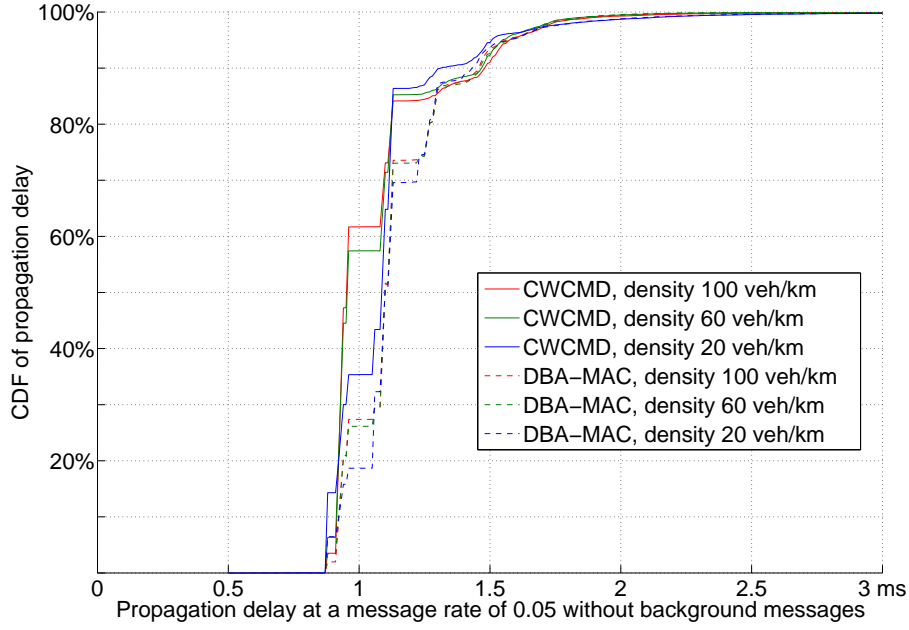


Figure 3.8: The CDF of propagation delay in both schemes at changing density with the rate of safety message generation being 0.05

than the one at the high density and therefore, the average distance between adjacent BMs is smaller than at the high density in both schemes.

Density per km	100	60	20
Delay /ms	1.065 ± 0.390	1.070 ± 0.360	1.096 ± 0.384
Retransmission times	5.51 ± 0.75	5.55 ± 0.74	5.77 ± 0.73
Distance between BMs /m	229.05 ± 7.86	222.97 ± 12.23	195.88 ± 35.11

Table 3.15: Average delay, retransmission time and distance between adjacent BMs in the CWCMD in various densities

Figure 3.9, table 3.17 and 3.18 show how the background messages (BGMSG) impact the system performance. With the increase of background message rate, the performance of safety message propagation is degraded. From table 3.8, we see that the length of the background message is five times as long as the safety message. A transmitted background message occupies the channel longer than a safety message. Therefore, with the increase of background messages, the rate of transmission failures and re-transmissions go up as well as the waiting time before transmissions. This account for the longer delay of safety messages. Even so,

Density per km	100	60	20
Delay /ms	1.141 ± 0.473	1.144 ± 0.280	1.156 ± 0.29
Retransmission times	6.03 ± 0.83	6.04 ± 0.84	6.15 ± 0.82
Distance between BMs /m	181.92 ± 59.62	180.21 ± 58.48	170.41 ± 57.57

Table 3.16: Average delay, retransmission time and distance between adjacent BMs in DBA-MAC in various densities

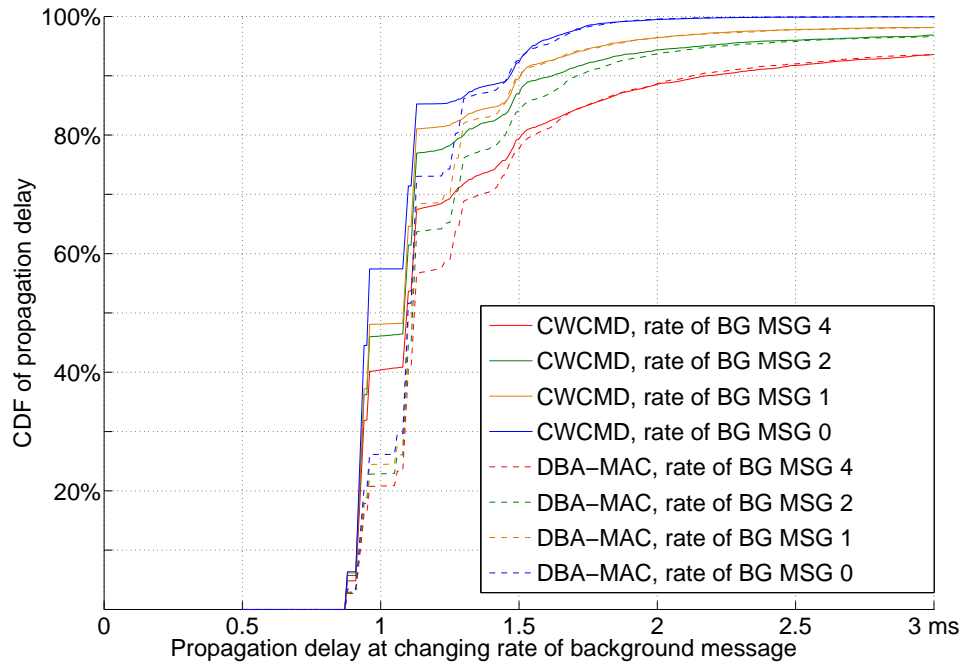


Figure 3.9: The CDF of propagation delay in both schemes in changing rate of BG msg with the rate of safety message being 0.05 at a density of 60

the performance in the CWCMD outperforms DBA-MAC at all rates of background message generation due to the longer distance between adjacent BMs.

Rate of BG MSG	0	1	2	4
Delay /ms	1.070 ± 0.360	1.210 ± 1.020	1.337 ± 1.481	1.641 ± 2.192
Retransmission times	5.58 ± 0.71	5.67 ± 0.79	5.71 ± 0.84	5.86 ± 0.99

Table 3.17: Average delay and retransmission time in CWCMD in various rates of background messages

Rate of BG MSG	0	1	2	4
Delay /ms	1.144 ± 0.280	1.290 ± 1.185	1.426 ± 1.503	1.688 ± 2.178
Retransmission times	6.04 ± 0.84	6.10 ± 0.89	6.17 ± 0.94	6.26 ± 1.03

Table 3.18: Average delay and retransmission time in DBA-MAC in various rates of background messages

It is shown in the results that the retransmission time of messages is not significantly increased but the mean of propagation delay is increased by up to some 40%. Before the message is broadcast, the message generator senses the channel and transmits it if the channel is idle. Due to the length of the background message, which is 5 times longer than the safety message, it occupies the channel longer and with the rise of background message rate the safety message generators have to wait for a longer time before broadcasting the message which leads to a prolonged delay.

3.6 Conclusion

In this chapter, a novel metric, the DEFT, for proactive routing protocols is proposed, which considers the impact of network formation on propagation delay. The metric reflects the message propagation more precisely than the delay only. In addition, the drawback of a routing protocol, DBA-MAC, is analysed. Randomness of CW selection is the predominant reason that a candidate with weak suitability is able to become the BM, which lowers the system performance. Therefore, a CW constraint scheme (CWC) and Minimum Distance as Criterion (MDC) are proposed to improve the system performance in terms of propagation delay and number of vehicles involved in the message transmission. The CWC is also applicable in the VANET protocols adopting the CW mechanism to distinguish candidates. With the combina-

tion of the CWC and the MDC, the CWCMD, the safety messages can be propagated faster than with DBA-MAC.

Chapter 4

Mathematical Models of DBA-MAC and the CWCMD, and Optimal Configuration of the System

4.1 Introduction

In the previous chapter, we summarised DBA-MAC, analysed its drawbacks and proposed an improved scheme to speed up message propagation. In this chapter, mathematical models for DBA-MAC and the CWCMD (DBA-MAC with CW Constraint scheme and Minimum Distance as criterion) are established based on statistical analysis, to predict and to estimate the BM selection performance as well as to validate the simulation results. The mathematical models indicate the winning probability of each suitable vehicle in a set of candidates. Numerical methods are used to calculate the winning probability, which is a function of vehicle density and relative distance. Comparison between simulation results and the analytical ones is presented.

We present the performance of DBA-MAC, the CWCMD and flooding, in terms of propagation latency, average transmission times and the DEFT (Delay taking into account the Effect of Formation Time). Results show that the CWCMD provides the best performance in terms of fast propagation. Besides, observation shows that the change of CW and length of CW selection, L , affect the performance of network formation time and propagation delay simultaneously in the CWCMD. The optimal performance of the DEFT is obtained by adjusting CW and L . Simulations are carried out in this chapter to acquire the system configuration of optimal performance.

In addition, it is usually assumed that the location of vehicles follows a Poisson distribution, particularly in network simulators in current literature. Yet, due to the existence of a security distance the Poisson distribution cannot describe the location accurately. A novel distribution of the following vehicles is proposed in this chapter, maintaining a security distance between adjacent vehicles in the same lane.

The first contribution in this chapter is the statistical models that estimate the winning probability of suitable candidates. The second contribution is the application of the proposed metric to the CWCMD to get the configuration of optimal performance by adjusting parameters related to CW. Further, a practical distribution of vehicles' location is proposed in this chapter which considers the security distance between adjacent vehicles in the same lane.

The rest of the chapter is organised as follows: section 4.2 describes the theoretical models of distance distribution in DBA-MAC and the CWCMD, with numerical results and comparison with simulation results. Section 4.3 describes the method and procedure to determine the system configuration of optimal performance, which balances the propagation delay and network formation time. In section 4.5, a novel location distribution of vehicles is proposed which incorporates a security distance between vehicles in the same lane and compares this with the case of no security distance. Section 4.5 draws conclusions.

4.2 Mathematical Models of DBA-MAC and the CWCMD

In DBA-MAC and the CWCMD, BMs forward the safety message as soon as they receive it, with no backoff time. The delay for each single message in unit distance (1 km) is, therefore, determined by the transmission time from the source to the last transmitter. With more BMs within the coverage range, the message is forwarded by more BMs and the delay will be increased. For example, a safety message may be forwarded by as few as 5 BMs or, say, 7 BMs to cover 1 km. The message propagation in the latter is approximately 40% longer than the one in the former. The average distance between adjacent BMs is inversely proportional to the number of BMs in a specific range. Therefore, the distance between adjacent BMs has an impact on the propagation delay.

To get the distance distribution of adjacent BMs, a mathematical model is proposed, which indicates the winning probability of each candidate in a set of suitable candidates in the BM selection phase. The winning probability is a function of the number of candidates, relative distance to the nearest BM, and the speed distribution. The suitability of each candidate is expressed as the maximum value of the contention window as is shown in Equation 4.1(DBA-MAC) and Equation 4.12(CWCMD). A numerical method is used to compute the winning probability in the radio range, which is the distance distribution of adjacent BMs.

4.2.1 Mathematical Models: DBA-MAC

In the BM selection phase of DBA-MAC, the candidate's suitability depends on its relative location to the nearest BM at the end of the period. The maximum backoff time, CW_i , for candidate i is,

$$CW_i = \left(1 - \frac{\Delta s_i + \Delta v_i t}{RR}\right) (CW_{max} - CW_{min}) + CW_{min} \quad (4.1)$$

The backoff time, $T_{backoff}$, of candidate i is the product of the slot time and a random value, CW'_i , which is uniformly distributed between 1 and CW_i ,

$$T_{backoff} = T_{slot} CW'_i \quad (4.2)$$

where CW'_i is a randomly-selected number from 1 to CW_i . In this thesis, it is called the countdown number.

The first candidate to finish backoff prior to others responds to the previous BM with a candidature message and becomes the next BM after receiving the ACK message from the previous BM. Other candidates suspend countdown and listen to the channel if they receive the candidature message. In other words, a candidate with a unique minimum CW'_i among all of the candidates becomes the next BM. If more than one candidate responds at the same time the contention procedure restarts and the candidates select backoff randomly again in this analysis. The winning probability is given by the probability that CW'_k of all the other candidates is greater than CW'_i . Therefore, the winning probability of candidate i is written as:

$$P_i(CW'_i) = P(CW'_1 > CW'_i, CW'_2 > CW'_i, \dots, CW'_k > CW'_i, k \neq i, k \in 1, 2, \dots, N) \quad (4.3)$$

Since CW'_i is randomly selected from 1 to CW_i , the distribution of CW'_i is the reciprocal of CW_i ,

$$p(CW'_i) = \frac{1}{CW_i} \quad (4.4)$$

Using Equation 4.3 and 4.4 and the theory from Proakis [59], the probability of candidate i winning in all cases is a weighted sum of the winning probability over all the possible CW'_i

and the weight for each case is the probability that the case occurs, which can be derived as Equation 4.5

$$\begin{aligned}
 P_i &= \sum_{CW'_i=1}^{CW_i} P_i(CW'_i)p(CW'_i) \\
 &= \frac{1}{CW_i} \sum_{CW'_i=1}^{CW_i} P(CW'_1 > CW'_i, CW'_2 > CW'_i, \dots, \\
 &\quad CW'_k > CW'_i, k \neq i, k \in 1, 2, \dots, N | CW'_i)
 \end{aligned} \tag{4.5}$$

where P_i defines the winning probability of candidate i . N is the total number of suitable candidates which are involved in the contention for the next BM, with CW'_k defining the randomly-selected value of candidate k .

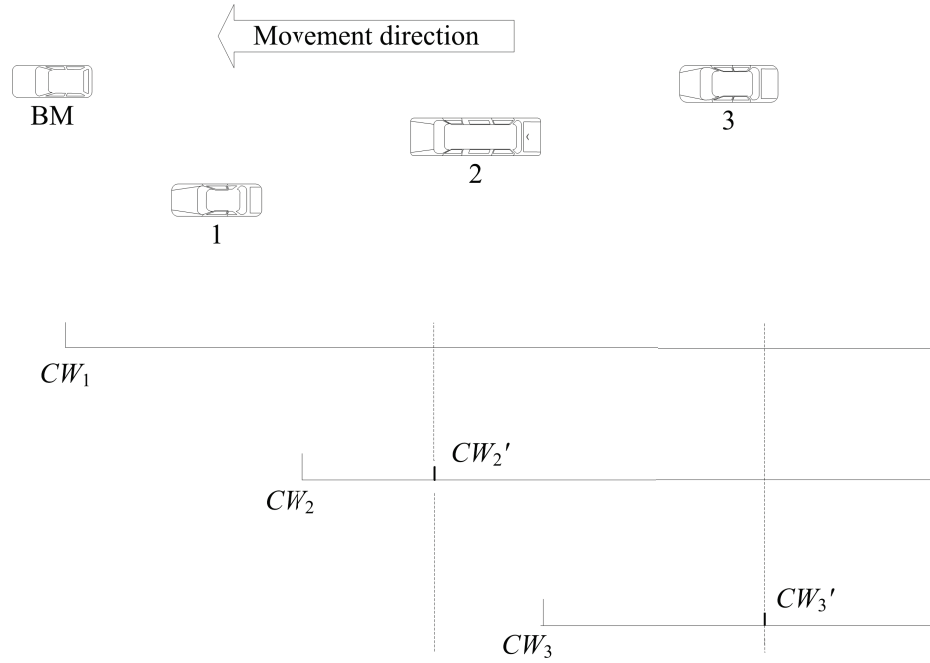


Figure 4.1: *Illustration of CW random selection*

Figure 4.1 illustrates how to calculate the winning probability for each individual candidate. Take candidate 3 for example, if candidate 3 wins in the contention with the countdown number CW'_3 ($1 \leq CW'_3 \leq CW_3$), the countdown number of other candidates will be greater than

CW'_3 .

Note that the winning probability can be zero. Take candidate 2 for example. We assume the countdown number of candidate 2 is CW'_2 . If $CW'_2 > CW_3$, all the possible countdown numbers for candidate 3 are smaller than CW'_2 . Candidate 2 with its countdown number being CW'_2 ($CW'_2 > CW_3$) is unable to finish backoff prior to candidate 3, and consequently, the winning probability of candidate 2 is zero.

The winning probability is acquired in the condition that the backoff time of the winner is the only minimum. If more than one candidate finishes backoff and responds to the BM simultaneously, collision occurs and the BM fails to receive the candidature message successfully. In the mathematical model, it is assumed that once collision occurs all the suitable candidates restart contention and select CW'_i again. The winning probability of candidate i in the re-selection procedure is as Equation 4.5 shows. The contention procedure continues until the unique winner is selected. In practice, if collision occurs, the BM fails to receive messages from candidates and it broadcasts the beacon again to restart the contention process which is reflected by the mathematical model.

4.2.2 Simplification of Mathematical Models for DBA-MAC and its Calculation

In the BM formation phase, the backoff time is related to the relative distance from the candidate to the last BM, the relative speed of the candidate and the maximum radio range of the BMs. In other words, the parameters required for the contention for each candidate can be determined by the candidate itself. No communication is required between the candidates until responding to the BM and, therefore, the candidates are independent of each other.

One property of joint probability distribution functions is that the joint probability function equals the product of the probability function of all variables if they are independent. For example, if variables X and Y are independent of each other, the joint probability function is the product of the individual probability functions,

$$P(X, Y) = P(X) P(Y) \quad (4.6)$$

According to the above property, the winning probability given a certain countdown number in Equation 4.3 is rewritten as follows,

$$\begin{aligned}
 P_i(CW'_i) &= P(CW'_1 > CW'_i) P(CW'_2 > CW'_i) \cdots P(CW'_k > CW'_i), k \neq i, k \in 1, 2, \dots, N \\
 &= \prod_{k=1, k \neq i}^N P(CW'_k > CW'_i)
 \end{aligned} \tag{4.7}$$

And Equation 4.5 is rewritten as follows

$$\begin{aligned}
 P_i &= \frac{1}{CW_i} \sum_{CW'_i=1}^{CW_i} P_i(CW'_i) \\
 &= \frac{1}{CW_i} \sum_{CW'_i=1}^{CW_i} \left(\prod_{k=1, k \neq i}^N P(CW'_k > CW'_i) \right)
 \end{aligned} \tag{4.8}$$

Equation 4.7 shows that the probability of a candidate winning with a specific countdown number can be expressed as the product of the probability that this candidate finishes backoff prior to all other candidates. Take candidate 3 in Figure 4.1 for example, the countdown number is CW'_3 . Candidate 3 becomes the next BM only if it finishes backoff prior to candidate 1 and 2. To get this probability, what we need is the winning probability of candidate 3 over each one. For any candidate, say candidate 1, if its countdown number is greater than CW'_3 , then candidate 3 responds to the BM prior to it. Therefore,

$$P(CW'_1 > CW'_3) = \frac{CW_1 - CW'_3}{CW_1} \tag{4.9}$$

Generalising the above equation, we get the following equation, for candidate i

$$P(CW'_k > CW'_i) = \begin{cases} \frac{CW_k - CW'_i}{CW_k} & CW_k > CW'_i \\ 0 & \text{otherwise} \end{cases} \tag{4.10}$$

Using Equation 4.10, the winning probability can be found in a simple way. Notice that if the countdown number of candidate i , CW'_i , is greater than the maximum countdown number of candidate k , CW_k , the winning probability of candidate i in this case is zero.

With the above equations, the winning probability of a specific candidate is able to be calculated. The statistical results of the winning probability as well as the distance distribution will be presented in the following sections.

4.2.3 Mathematical Models: the CWCMD

The basic mechanism in both DBA-MAC and the CWCMD, that candidates choose a countdown number for a backoff time to select a winner, is the same; therefore, they share a similar mathematical model. Yet, a feature of the CWCMD leads to the changes in the winning probability, i.e., the range of CW selection, which accounts for the change in the mathematical model.

In DBA-MAC, the possible countdown number of the backoff ranges from 1 to CW_i for candidate i . The CWCMD raises the lower boundary such that the range of CW selection is a positive integer, L . The possible countdown number of candidate i is from $CW_i - L + 1$ to CW_i . Consequently, the winning probability in Equation 4.8 is rewritten,

$$P_i = \frac{1}{L} \sum_{CW'_i = CW_i - L + 1}^{CW_i} \left(\prod_{k=1, k \neq i}^N P(CW'_k > CW'_i) \right) \quad (4.11)$$

In addition, the suitability ranking of candidates leads to the change of the mathematical model:

$$CW_i = \left(1 - \frac{\min(\Delta s_i, \Delta s_i + \Delta v_i t)}{RR} \right) (CW_{max} - CW_{min}) + CW_{min} \quad (4.12)$$

where Δs_i is the relative distance from candidate 1 to the BM at the beginning of the period, and Δv_i is the relative speed between candidate 1 and the BM. t is the period of the BM network. Figure 4.2 illustrates the calculation of the winning probability in the CWCMD. The smallest countdown number of candidate 1 is $CW_1 - L + 1$, which is greater than the greatest countdown number of candidate 2, CW_2 . The probability of candidate 1 winning over candidate 2 is zero,

$$P(CW'_2 > CW'_1) = 0 \quad (4.13)$$

The range of CW, L , is a value equal to or less than CW_{min} , which is set to 15 in the system. This is because the minimum CW_i for any candidate is CW_{min} according to Equation 4.12.

All the candidates share the same range of CW selection due to L . In the next section, the impact of L on system performance will be discussed.

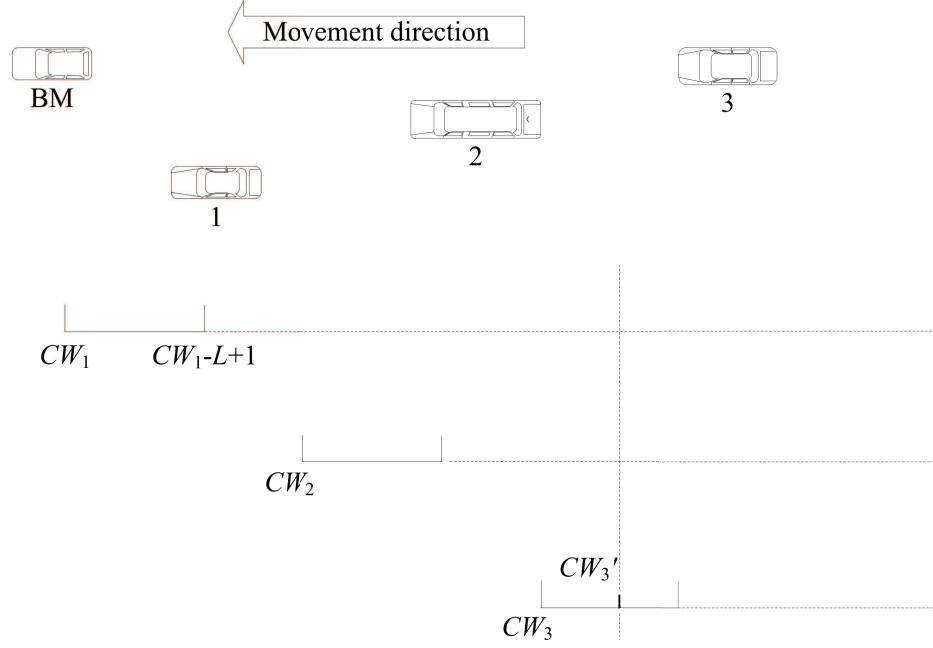


Figure 4.2: Illustration of CW constraint

4.2.4 Numerical Results of mathematical models and Simulation Results

Deduction in this chapter shows models which are used to predict the performance of the BM selection in DBA-MAC and the CWCMD. Jointly with the numerical results in this part, the models are able to estimate and validate the BM selection in both DBA-MAC and the CWCMD.

4.2.4.1 Methodology

The PDF (Probability Density Functions) of the distance of the adjacent BMs is calculated within the transmission range with 1 metre being the interval used in this thesis.

Note that the results in this chapter present the instantaneous traffic condition. A speed is allocated to each vehicle to predict its location at the end of the period. The mobility of vehicles is unnecessary and neglected, since the instantaneous traffic condition also applies to any time instance throughout the period.

Only the procedure of network formation is simulated in this part. Once a BM vehicle broadcasts a beacon message to select the next BM, the following vehicles within its transmission range calculate their suitability based on the selection criterion. In the simulation results of this part, the candidates are contending to be the BM by randomly selecting a back off time, which is the same as the simulations in Chapter 3. The difference between the results here and those in Chapter 3 is that the phase of message propagation is excluded, since message propagation makes no impact on the BM selection. In the case of mathematical models, the winner and the winning probability are calculated from the deducted expressions.

The Monte Carlo method is used to obtain the results. The random elements in each of the iterations are the location and speed of the vehicles. The difference between the simulation in this chapter and the one used in Chapter 3 is that the mobility is considered here to predict the location of vehicles at the end of each period, yet the vehicles do not need to move, since the results here show the instantaneous traffic condition.

4.2.4.2 System Configuration

The parameters used for calculating the numerical results, and the simulation, are given in Table 4.1.

density	60 per km	speed	64 ± 6 mph
lanes	4	L	4
CW_{max}	1023	CW_{min}	15

Table 4.1: *System Configuration*

In Table 4.1, the CW range, L , applies only to the CWCMD, since there is no selection constraint in DBA-MAC. The location of vehicles follows a Poisson distribution in the numerical results. For the simulation, as adjacent BMs in the same lane cannot be less than the security distance, i.e. 50 metres, the distribution is not Poisson distribution for short distance.

To get the numerical results, the location and speed of BMs and a set of candidates are predefined to be able to derive the winning probability. By adding the results of iterations and normalising the results, a statistical result is obtained. In the simulation, once the location and speed of vehicles are predefined, the candidates start BM network formation using the contention schemes instead of calculating the result from probability theory. The results are

presented below.

4.2.4.3 Theoretical Comparison between DBA-MAC and the Proposal

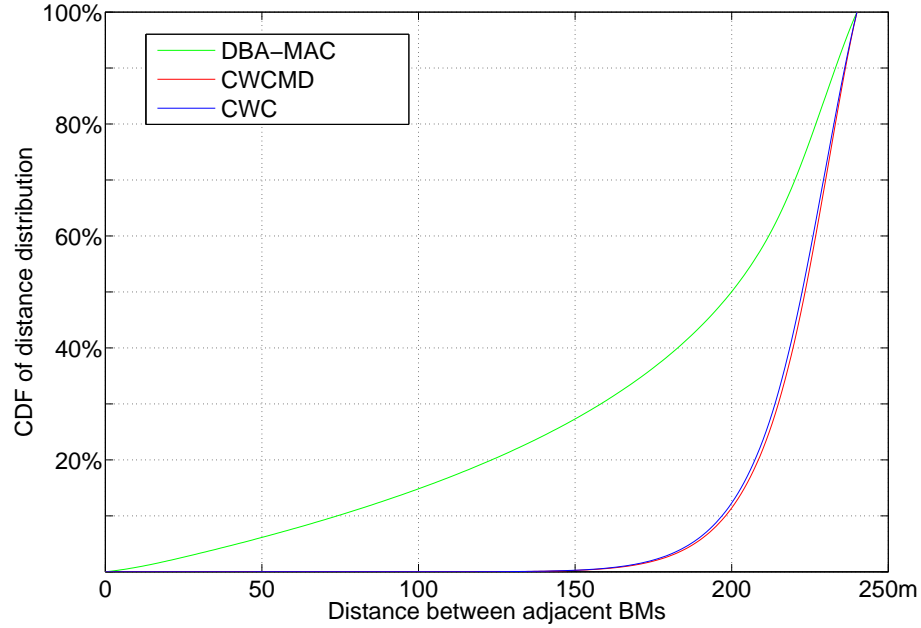


Figure 4.3: *The CDF of the distance between adjacent BS in both DBA-MAC and the CWCMD in numerical results*

The Cumulative Distribution Function (CDF), of distance between adjacent BSs in both schemes are presented in Figure 4.3. In DBA-MAC, the distance between adjacent BSs spreads from zero to the radio range. The gradient of the CDF rises with the increase of distance. This is because in DBA-MAC the candidates with weaker suitability have greater CW value and the probability that a vehicle with weaker suitability finishes backoff prior to a vehicle with greater suitability is small. Yet, the vehicle with weaker suitability still has a chance to win the contention. Therefore, the CDF curve is non-zero at any distance. While in the CWCMD, the lower boundary of candidates with weak suitability is $CW_i + L - 1$ instead of 1 in DBA-MAC. Such candidates with weak suitability are unable to finish backoff prior to the candidates with greater suitability, i.e. those whose maximum countdown number is less than $CW_i + L - 1$. As the curve reflects, the CDF of distance less than 150 metres in CWCMD is almost zero. This figure shows that the CWCMD results in a longer distance between adjacent BSs than DBA-MAC.

By examining the PDF curves in Figure 4.4, a reduction in probability can be observed close to the radio range. In the BM selection phase in both schemes, the candidates moving out of a BM's radio range at the end of the period are excluded from the contention. They are the reasons for the sharp slope in both curves.

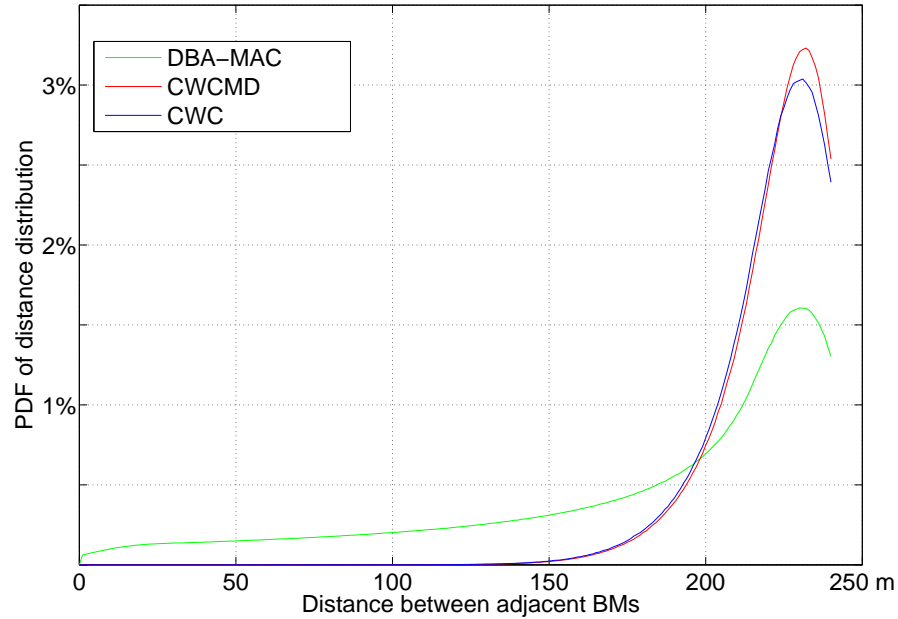


Figure 4.4: *The PDF of the distance between adjacent BM in both DBA-MAC and the CWCMD in numerical results*

Figure 4.3 shows that the majority of performance improvement is due to the CW constraint scheme (CWC) in the CWCMD. The improvement of the average BM distance is approximately 0.7 metres by the change of SI, i.e., minimum distance as criterion (MDC) in the CWCMD. Analysis in Chapter 3 indicates that the change of SI affects the candidate with the highest suitability only when the overlap of the relative distance throughout the period exists between the candidate with the highest suitability and other candidates, esp. in the CW constraint scheme. The case of overlap occasionally occurs and this is the reason that the MDC improves the system performance slightly.

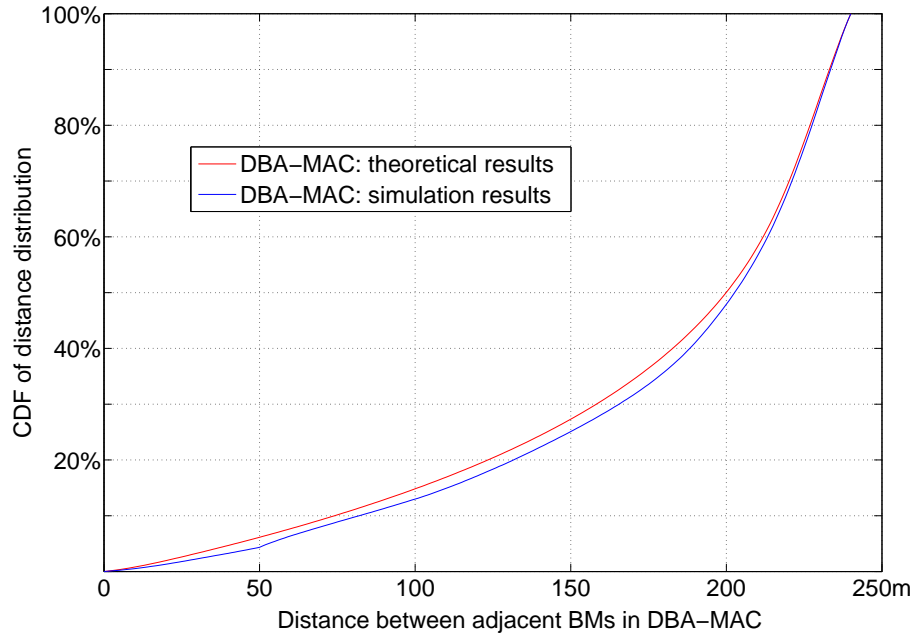


Figure 4.5: Comparison of the distance CDF between numerical results and simulation in DBA-MAC

4.2.4.4 Comparison between Theoretical Results and Simulation Results

Figures 4.5 and 4.6 are the comparison between numerical results and simulation results in both schemes. Analysis and simulation differ from each other in the distance distribution only. In the analysis, all the vehicles on the highway follow a Poisson distribution, the parameters of which are specified by the vehicle density. While in the simulation, the vehicles follow a Poisson-like distribution, with a security distance existing between consecutive vehicles in the same lane. The security distance is set to 50 metres at the density of 60 vehicles per kilometre on four lanes. The security distance is the approximate distance that the vehicle goes through in 2 seconds.

In Figure 4.5, the gradient changes at 50 meters. The gap between simulation and analysis is insignificant and the PDF curves show the change more clearly, as in Figure 4.7. The security distance accounts for the spike at 50 metres in the PDF of simulation results of DBA-MAC, as is shown in figure 4.7. In the simulation, BMs in the range from 0 and 50 metres corresponds to the vehicles in different lanes. From 50 metres on, BMs can be in the same lane of the upstream BM, and these vehicles are the source of spikes in the simulation curve.

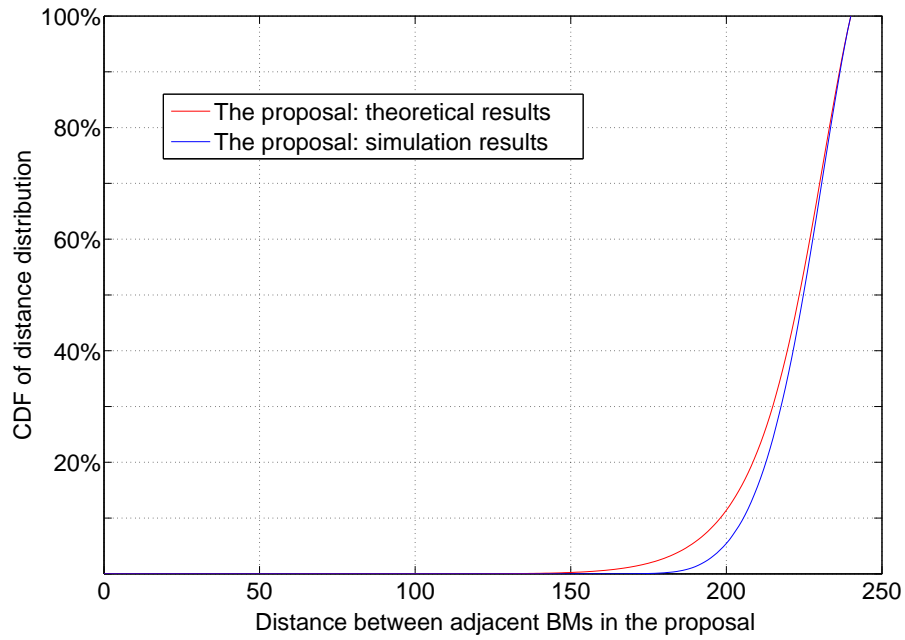


Figure 4.6: Comparison of the distance CDF between numerical results and simulation in the CWCMD

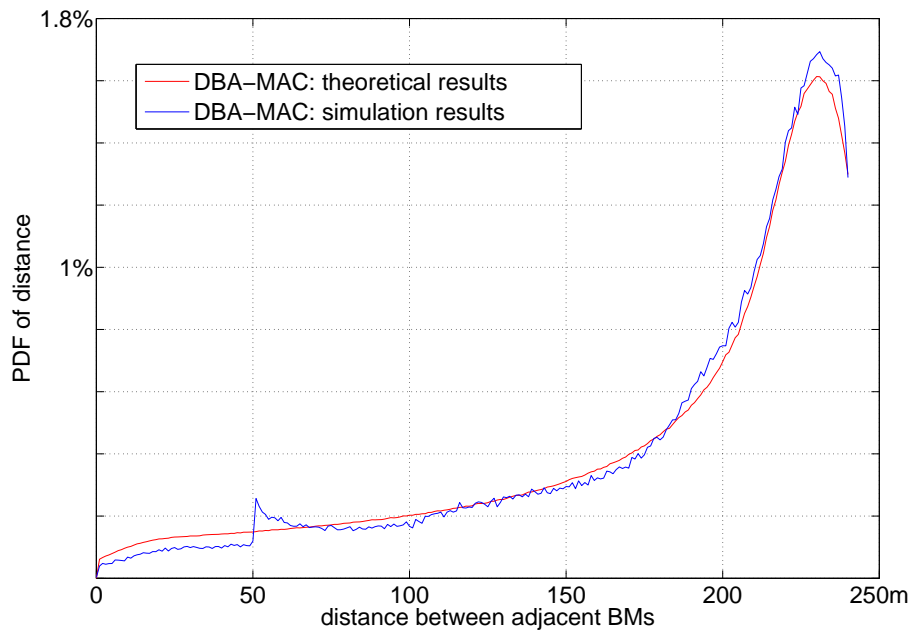


Figure 4.7: Comparison of the distance PDF between numerical results and simulation in DBA-MAC

It is noticed that a gap exists in the CDF between numerical results and simulations of the CWCMD. This is mainly due to the location distribution of the vehicles. This can be explained using order statistics.

To show the impact of the location distribution on the distance distribution of BMs, the speed of each vehicle is set to zero. In this case, the farthest candidate is the best candidate to be the next BM according to the suitability criterion and the distribution of the farthest candidate is the distance distribution of adjacent BMs. At a density of 60 veh/km, there are approximately 14 vehicles within the radio range on average. The location distribution of the k th candidate among n candidates is written as Equation 4.14 from the theory of order statistics [60],

$$Pr(k) = \frac{n!}{(k-1)!(n-k)!} F(x)^{k-1} [1 - F(x)]^{n-k} f(x) \quad (4.14)$$

The distribution of the last candidate in n candidates is

$$Pr(n) = n [F(y)]^{n-1} f(y) \quad (4.15)$$

where $f(y)$ is the PDF of the vehicles location, $F(y)$ is the CDF of the vehicles location. The CDF of the last candidate in both order statistics and the simulation of the CWCMD with no relative speed is shown in Figure 4.8.

Between the results of order statistics and the simulation of the CWCMD, the main difference lies in the location distribution of vehicles. In numerical results, all the vehicles follow a Poisson distribution. While in the simulation they follow a Poisson-like distribution with security distance. The security distance in the simulation causes the difference between the location PDF/CDF of all candidates in the simulation and numerical results. In the numerical results of order statistics, the 14th candidate after the BM is the farthest candidate and the winner. Its PDF is expressed as Equation 4.15 where $n = 14$. In the simulation, however, due to the security distance, both $f(y)$ and $F(y)$ change, which leads to the change of $Pr(14)$ in the simulation. In addition, in the simulation without speed, due to the randomness of the vehicle distribution, it is hard to guarantee the last candidate within the radio range of a BM is the specific candidate, i.e. 14th candidate. It may be greater or less than 14. This also changes the distribution of adjacent BMs. The change of location distribution of vehicles also accounts for the gap of the CDF of DBA-MAC in both the simulation and analysis.

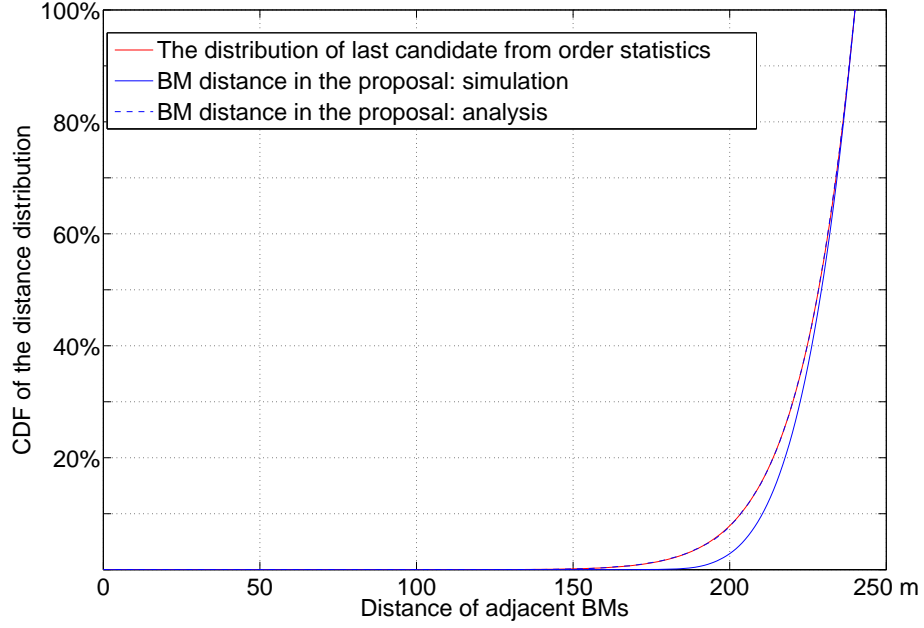


Figure 4.8: *The CDF comparison between the simulation of the CWCMD with no speed distribution and the last candidate in order statistics*

4.3 Optimal Configuration Based on the Proposed Metric

In the CWCMD, the main feature is the confined range of CW selection. If candidate i is the winner in the contention and the length of CW selection is set as L , the possible backoff time for the winner is from $CW_i - L + 1$ to CW_i . Backoff time and transmission time of the beacon and ACK by each winning candidate define the network formation time. Hence, CW_{max} and L which determine the backoff time also relate to formation time. As for the propagation delay, it is related to the number of times a message is forwarded and therefore the average distance in between adjacent BSs matters. CW_{max} takes an impact on the ability of the system to distinguish candidates. With a smaller CW_{max} and greater L , multiple candidates may have the same upper boundary of the countdown number and there will be a high probability of identical countdown numbers, which reduces the probability of the most suitable candidates to win, resulting in a longer propagation delay. To show the impact of CW_{max} and L on formation time and delay, a series of simulations are conducted. In the simulation, we show the performance in terms of network formation time and average distance between adjacent BSs in the CWCMD for various CW_{max} and L . The value of CW_{max} is $2^n - 1$. To improve

the accuracy of results, the median points between consecutive CW_{max} are also adopted as CW_{max} . And L changes from 1 to CW_{min} , which is 15 in the configuration.

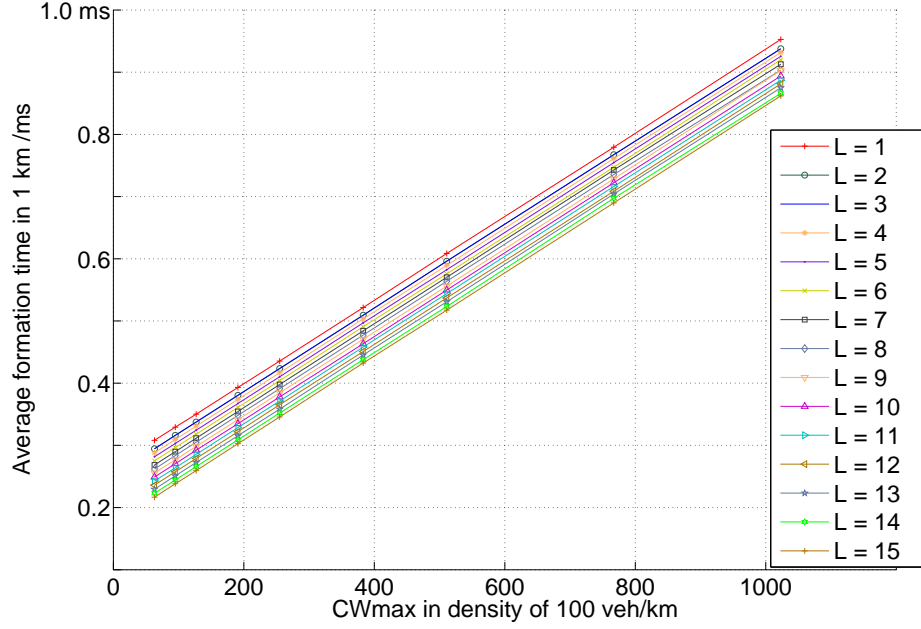


Figure 4.9: Impact of CW_{max} and L on the formation time

Figures 4.9 and 4.10 present the effect of changing parameters on the formation time and the average distance between adjacent BMs at the density of 100 veh/km.

Figure 4.9 indicates that a larger CW_{max} results in a longer formation time in the CWCMD. In the CWCMD, CW_i is a linear function of CW_{max} as Equation 4.12 shows. This accounts for the relation between CW_{max} and network formation time. It can be seen that at the same CW_{max} a smaller range of CW selection increases the formation time. This is because the minimum backoff time for each BM is $CW_i - L + 1$ and a smaller L increases the minimum backoff time for each winner in the BM selection phase. As L increases, the winning candidate is able to respond to the BM in a shorter time which reduces the backoff time as well as the formation time.

The effect of changing CW_{max} and L on the average distance between adjacent BMs is presented in Figure 4.10. The average distance rises with an increasing CW_{max} . This is because CW_{max} determines the ability to distinguish between candidates. The maximum countdown number for candidate i , CW_i , is proportional to CW_{max} as Equation 4.1 and 4.12 show. We

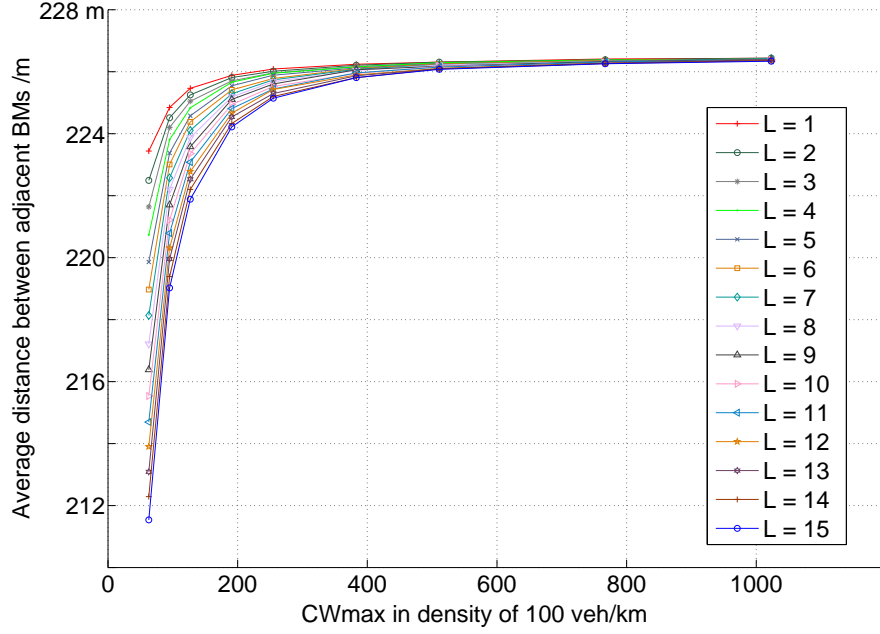


Figure 4.10: Impact of CW_{max} and L on the average distance between adjacent BMs

define a suitability index for candidate i as SI_i ,

$$SI_i = \frac{\Delta s_i + \Delta v_i t}{RR}, \text{ for DBA-MAC} \quad (4.16)$$

$$SI_i = \frac{\min(\Delta s_i, \Delta s_i + \Delta v_i t)}{RR}, \text{ for CWCMD} \quad (4.17)$$

Therefore, the relation between CW_i and SI_i is

$$CW_i = (1 - SI_i)(CW_{max} - CW_{min}) + CW_{min} \quad (4.18)$$

The difference between the maximum countdown number of candidate i and k , ΔCW_{ik} is therefore given by

$$\Delta CW_{ik} = (SI_k - SI_i)(CW_{max} - CW_{min}) \quad (4.19)$$

Equation 4.19 shows that for two candidates the ratio between ΔCW_{ik} and the suitability difference is $CW_{max} - CW_{min}$. If CW_{min} is set to be a constant, CW_{max} determines the ratio. In other words, the candidates are able to be distinguished by a large CW_{max} even if the gap

in the SI is small. Hence, the value of CW_{max} is the crucial factor to distinguish the candidates. This explains the reduction of the average distance at a smaller CW. With weak ability to distinguish between candidates, collision between the responses from candidates arises with relatively high probability which increases the possibility that candidates with weak suitability win the contention. The average distance between adjacent BMs decreases accordingly.

In addition, for each specific CW_{max} , the selection range L determines whether there exists an overlap of backoff time of candidates and how large the overlap is, as is shown in Figure 4.11. With longer L , the overlap of possible backoff time among candidates rises, which increases the

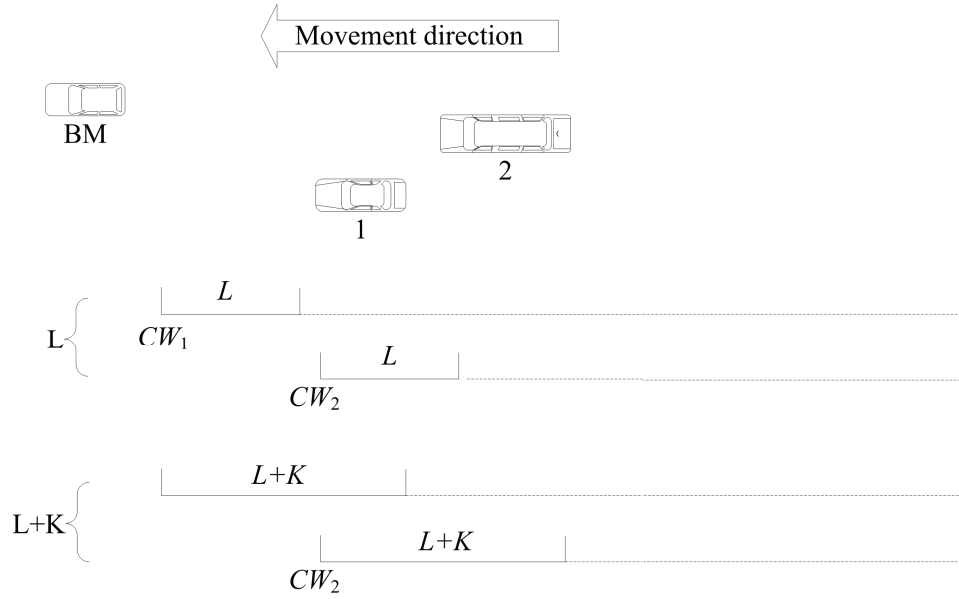


Figure 4.11: Impact of L on the BM selection

probability that candidates with a weaker suitability will win in the contention. This accounts for the reduction of the average distance between adjacent BMs.

As CW_{max} decreases, the ability of the system to distinguish between candidates becomes weaker. An increasing number of candidates have a similar countdown number with the decrease of CW_{max} , which also raises the winning probability of candidates with weak suitability, as is shown in Figure 4.12. This is the reason that the average distance between adjacent BMs decreases more with a longer L as CW_{max} decreases.

Figures 4.9 and 4.10 reveal that with the increase of CW_{max} , both the formation time and the average distance are increased. Balancing the formation time and the average distance is the

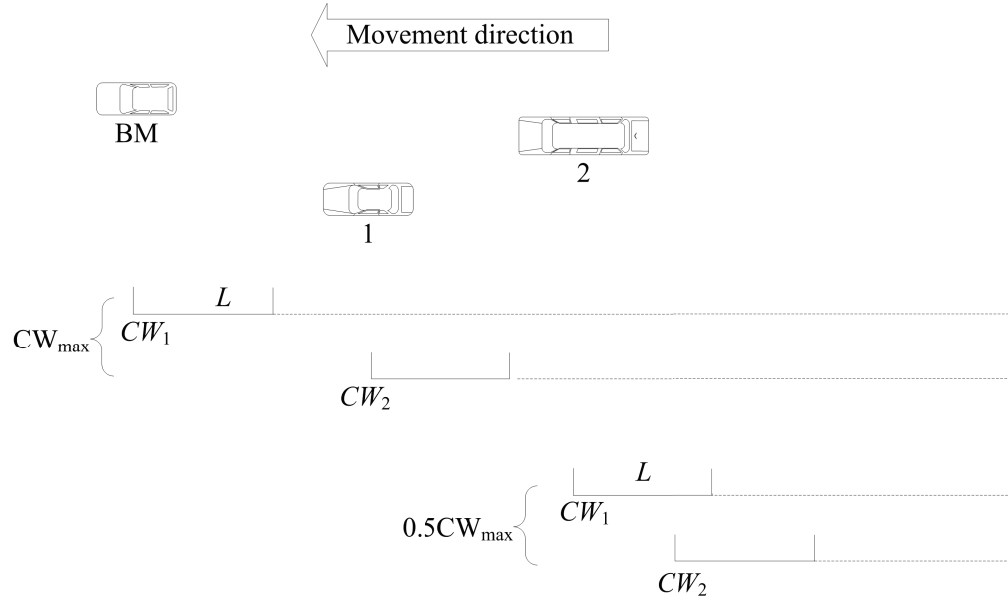


Figure 4.12: Impact of changing CW_{max} on the BM selection as L is a constant

key in the optimisation.

Figure 4.13 presents the performance of different CW_{max} and L in terms of DEFT. All 6 curves are concave, although at density of 60 and 100 the increase after $CW_{max} = 255$ is small. At density of 20, the minimum delay occurs when $CW_{max} = 127$, $L = 1$ and at density 60 and 100, it is when $CW_{max} = 255$, $L = 1$. In all the curves, the descending part before the minimum is due to the increase of the average distance between adjacent BMs. An increase of the average distance makes a more significant contribution to the proposed metric compared to formation time. After the minimum the curves rise with the increase of CW_{max} . This is because from the minimum point the change of CW_{max} affects the distance between adjacent BMs little while the formation time of the network still has an impact on DEFT.

It is noticed that at a low density, e.g. 20 veh/km, the ascending trend after the minimum point is more significant than the one at higher density. At a low density, since the location distribution of vehicles is more sparse, the range of possible distance between adjacent BMs is wider than at a higher density, which expands the formation time on average. Figure 4.14 shows that the system spends increasing time to form the network from the high density to the low density.

Therefore, according to the analysis, the optimal performance of the system depends on the density. At high density, e.g. 60 and 100 veh/km, to get the optimal performance, CW_{max} is set

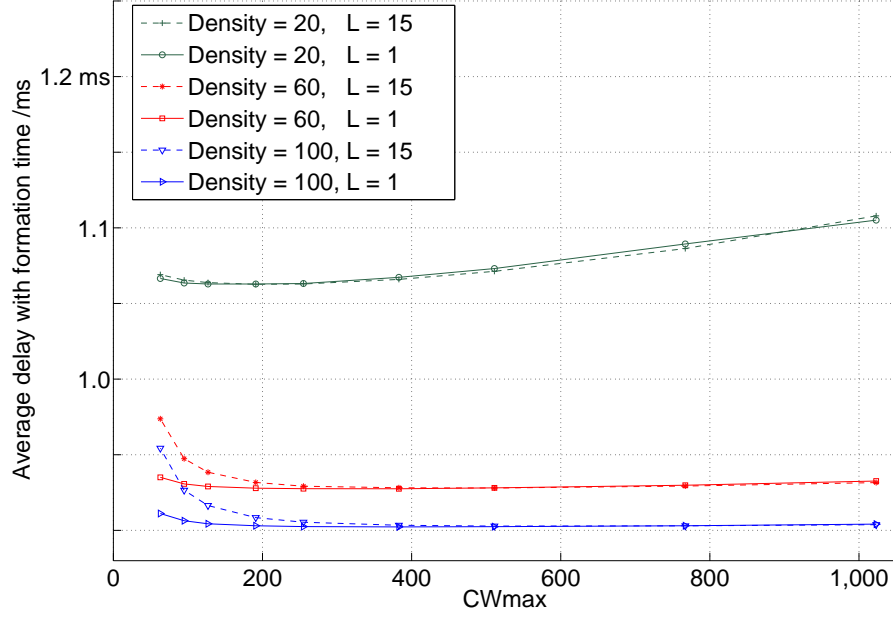


Figure 4.13: The performance of the CWCMD at all densities with change of CW_{max} and L

to 255 and L is 1. While at the low density, CW_{max} can be set to 127 and L to 1. Accordingly, with density diminishing, decreasing CW_{max} is the method to get the optimal performance of the system. In all cases, confining the randomness of CW selection is an approach to improve the performance of the BM selection.

4.4 Location Distribution with Consideration of Security Distance

The results in Chapter 3 and in this chapter show that the difference between the simulation and the numerical results stems from the ideal location distribution, in which the inter-vehicle space is assumed to be exponentially distributed and the security distance is neglected. A location distribution which incorporates the security distance among adjacent vehicles in the same lane is proposed in this section. The distribution aims to provide a more accurate way to estimate the location of the vehicles in the numerical results.

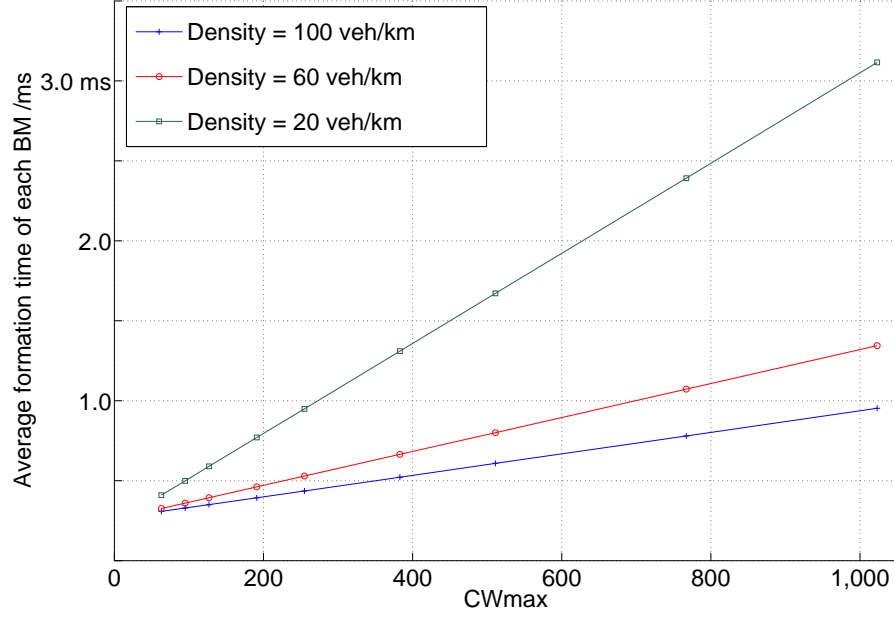


Figure 4.14: Impact of the vehicle density and CW_{max} on formation time

4.4.1 Analysis of the Existing Location Distribution

In the previous research in this chapter, it is assumed that the vehicles on the highway follow a Poisson Distribution in the numerical results. The results in Chapter 3 and in this chapter indicate that in a realistic scenario, in which the location distribution is not the ideal Poisson distribution, the system performance is affected, as well as the distribution of BMs. The gap between the simulation results and the numerical results is caused by the security distance of the location distribution in the simulation. In this section, the location distribution of each specific following vehicle after a reference vehicle is derived, where a security distance between the adjacent vehicles in the same lane is maintained.

In the ideal case, the vehicles on the road follow a Poisson distribution,

$$PD(k, x) = \frac{(\rho x) e^{-\rho x}}{k!}, k \geq 0 \quad (4.20)$$

where ρ is the vehicle density in veh/m and $PD(k, x)$ is the probability that there are k vehicles in a segment of road of x -metre length. If the vehicles' location follows a Poisson distribution, then the distance interval between consecutive vehicles is exponentially distributed. The distri-

bution of the distance between consecutive vehicles, $ED(x)$, is

$$ED(x) = \rho e^{-\rho x} \quad (4.21)$$

For the n th following vehicle, its distance from the lead vehicle is the sum of n independent distances. This is given by an Erlang distribution

$$ErD(x, n) = \frac{\rho^n x^{n-1} e^{-\rho x}}{\Gamma(n)} \quad (4.22)$$

where $\Gamma(n)$ is the Gamma function.

It is noted that the vehicles on the road are distributed on the lanes equally and independently, regardless of the lane of the vehicles ahead. Thus, it is possible in the model that the distance between two consecutive vehicles is smaller than the security distance, despite the vehicles being located in the same lane. The occurrence of this case is related to the number of lanes, with a higher probability in the case of fewer lanes. The gap between numerical results and practice accumulates with any increase of the vehicle index n . Neglecting the security distance leads to obvious difference of vehicle distribution, which is embodied in the BM selection in both DBA-MAC and the CWCMD, as is shown in the previous results in this chapter.

4.4.2 The Proposed Distribution

The main difference between the proposed distribution and the exponential distribution lies in the consideration of the security distance between adjacent vehicles in the same lane. In the exponential distribution, the distance between adjacent vehicles in the same lane is neglected, which is far from being the practical case. The basic assumption in the proposed distribution is that the security distance is set as the minimum value of the distance between adjacent vehicles and this distance still follows an exponential distribution. The proposed distribution is given the name EDSL, short for Exponential Distribution with consideration of Security distance and Lanes.

The other difference is that in the proposed distribution the lanes of the road are considered. A vehicle is either in the same lane as another one, or is on a different lane. The movement and location of vehicles on different lanes are independent.

4.4.2.1 Location Distribution of Vehicles on the Same Lane as the Reference Vehicle

For adjacent vehicles in the same lane, the distance between them incorporates two components, i.e. the security distance and the additional distance. The part of the security distance is a predefined constant related to the vehicle density. The part of the additional distance follows an exponential distribution. In other words, the distance between adjacent vehicles in the same lane follows an exponential distribution with shift, that is

$$f_s(1, x) = \rho e^{-\rho(x-SD)} H(x - SD) \quad (4.23)$$

where $f_s(1, x)$ is the PDF of the distance between adjacent vehicles in the same lane. $f_s(1, x)$ also represents the location distribution of the 1st following vehicle in the same lane as the reference vehicle. $f_s(n, x)$ indicates the location distribution of the n th following vehicle in the same lane as the reference vehicle. The reference vehicle can be any vehicle that is on the road. x , a non-negative value, is the distance between two vehicles and at the location of the reference vehicle $x = 0$. The distance x is the distance between the projections of two vehicles on the roadside instead of the physical distance between the vehicles. $H(\cdot)$ represents the heaviside step function, $H(x) = 1$ as $x \geq 0$; otherwise, $H(x) = 0$. Equation 4.23 indicates that the location distribution of the 1st following vehicle after the reference vehicle is an exponential distribution with a shift along the reverse direction of movement.

Since the relation in equation 4.23 applies to all the vehicles in the same lane, the distribution of the distance from the reference vehicle to the 2nd following vehicle can be obtained by convolution:

$$f_s(2, x) = f_s(1, x) * f_s(1, x) = \rho^2 e^{-\rho(x-2SD)} (x - 2SD) H(x - 2SD) \quad (4.24)$$

In the same way, the distribution of the 3rd and 4th following vehicles are

$$f_s(3, x) = f_s(1, x) * f_s(2, x) = \frac{\rho^3}{2} e^{-\rho(x-3SD)} (x - 3SD)^2 H(x - 3SD) \quad (4.25)$$

$$f_s(4, x) = f_s(1, x) * f_s(3, x) = \frac{\rho^4}{6} e^{-\rho(x-4SD)} (x - 4SD)^3 H(x - 4SD) \quad (4.26)$$

The location distribution of the n th following vehicle is

$$f_s(n, x) = \frac{\rho^n}{\Gamma(n)} e^{-\rho(x-nSD)} (x - nSD)^{(n-1)} H(x - nSD) \quad (4.27)$$

Equation 4.27 presents the PDF of the n th following vehicle after any vehicle in the same lane. Therefore, the CDF of the n th following vehicle is

$$\begin{aligned} F_s(n, x) &= \int_0^x f_s(n, y) dy \\ &= \frac{\rho^n}{\Gamma(n)} e^{-\rho x} \sum_{i=1}^n \left(\frac{\prod_{j=1}^{i-1} (n-j)^{\text{sgn}(i-1)}}{\rho^i} x^{n-i} \right) \end{aligned} \quad (4.28)$$

where $\text{sgn}(x)$ represents a sign function. Equation 4.28 and equation 4.27 apply for vehicles on each individual lane.

4.4.2.2 Location Distribution of Vehicles on a Different Lane from the Reference Vehicle

The distance from the n th following vehicle ($n \geq 2$) in a different lane to a reference vehicle is the sum of 1) the distance from the 1st following vehicle in a different lane to the reference vehicle and 2) the distance from the 1st following vehicle to the n th following vehicle in the same lane. The distribution of the latter distance has been obtained in the last section. The distance distribution between the reference vehicle to the 1st following vehicle in a different lane will be shown in the following section.

The movement and location of the reference vehicle are independent from the 1st following vehicle in a different lane. Figure 4.15 provides an illustration of the distance between the reference vehicle and the 1st following vehicle in a different lane.

As is shown in figure 4.15, the distance from the reference vehicle a in lane 1 to the 1st following vehicle b in lane 2 is x . The distance from vehicle b to vehicle c , the one that is ahead in the same lane, is z . And the distance from vehicle a to c is y . Therefore, we have $x = z - y$. Since the distance of adjacent vehicles in the same lane follows an exponential distribution with shift, as has been shown in the previous section, the distribution of z is

$$f_Z(z) = \rho e^{-\rho(z-SD)} H(z - SD) \quad (4.29)$$

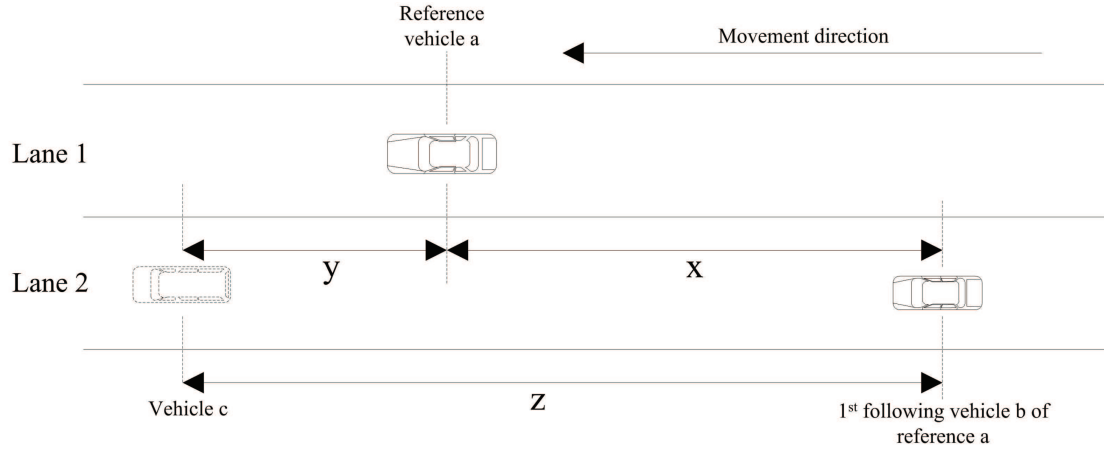


Figure 4.15: Illustration of the distance from the reference vehicle to the 1st following vehicle in a different lane

The movement and location of vehicles in different lanes are independent; therefore, vehicle a can be anywhere between vehicle b and c . The location of reference vehicle a to vehicle c , y follows a uniform distribution of z ,

$$f_Y(y) = \begin{cases} \frac{1}{z} & y \in [0, z] \\ 0 & \text{otherwise} \end{cases} \quad (4.30)$$

The CDF of the distance from reference vehicle a to vehicle b , x , is given by:

$$\begin{aligned} F_d(1, x) &= F_X(x) \\ &= P(z - y \leq x) \end{aligned} \quad (4.31)$$

$$= P(y \geq z - x) \quad (4.32)$$

$$= \iint f(y, z) dy dz \quad (4.33)$$

$$= \iint f_Y(y) f_Z(z) dy dz \quad (4.34)$$

Equation 4.31 is discussed in two conditions, i.e., $x \geq SD$ and $x < SD$. In the case of $x \geq SD$,

$$\begin{aligned} F_X(x) &= \iint f_Y(y)f_Z(z)dydz \\ &= \int_{SD}^x \int_0^z f_Y(y)dyf_Z(z)dz + \int_x^{+\infty} \int_{z-x}^z f_Y(y)dyf_Z(z)dz \end{aligned} \quad (4.35)$$

$$= \int_{SD}^x \rho e^{-\rho(z-SD)} dz + \int_x^{+\infty} \frac{x \cdot \rho e^{-\rho(z-SD)}}{z} dz \quad (4.36)$$

$$= 1 - e^{-\rho(x-SD)} + x\rho e^{\rho SD} E_1(x\rho) \quad (4.37)$$

where E_i and E_1 are exponential integrals, $E_i(x) = -\int_{-x}^{\infty} \frac{e^{-t}}{t} dt$ and $E_1(x) = \int_1^{\infty} \frac{e^{-tx}}{t} dt$. As $x < SD$,

$$\begin{aligned} F_X(x) &= \iint f_Y(y)f_Z(z)dydz \\ &= \int_{SD}^{+\infty} \int_{z-x}^z f_Y(y)dyf_Z(z)dz \end{aligned} \quad (4.38)$$

$$= x\rho e^{\rho SD} E_1(\rho SD) \quad (4.39)$$

Combining Equation 4.35 and Equation 4.38, the CDF of the distance from reference vehicle a to the 1st following vehicle b in a different lane is

$$F_d(1, x) = \begin{cases} x\rho e^{\rho SD} E_1(\rho SD) & 0 \leq x < SD \\ 1 - e^{-\rho(x-SD)} + x\rho e^{\rho SD} E_1(x\rho) & x \geq SD \end{cases} \quad (4.40)$$

Therefore, the PDF of the distance x is

$$f_d(1, x) = \begin{cases} \rho e^{\rho SD} E_1(\rho SD) & 0 \leq x < SD \\ \rho e^{-\rho(x-SD)} + \rho e^{\rho SD} E_1(x\rho) - x\rho e^{\rho SD} E_0(x\rho) & x \geq SD \end{cases} \quad (4.41)$$

where $E_0(x\rho) = \frac{e^{-x\rho}}{x\rho}$.

$F_d(1, x)$ and $f_d(1, x)$ present the CDF and the PDF of the distance between the reference vehicle to the 1st following vehicle in a different lane. To obtain the distribution of the n th following vehicle in a different lane, the distribution of the following vehicles in the same lane is adopted.

$$f_d(n, x) = f_d(1, x) * f_s(n - 1, x) \quad (4.42)$$

$$F_d(n, x) = \int_0^x f_d(1, y) * f_s(n - 1, y) dy \quad (4.43)$$

where $f_s(n - 1, x)$ is the PDF of the $(n - 1)$ th following vehicle in the same lane.

4.4.2.3 Location Distribution of the n th Following Vehicles Regardless of Lanes

The n th vehicle from the reference vehicle is the one which is the n th closest to the reference vehicle in the following direction, regardless of the lane of vehicles. The location distribution of the n th following vehicle is deducted based on the location distribution of the vehicles in the same lane and in the different lanes to the reference vehicle, using the theory of order statistics.

The location of the reference vehicle is assumed to be 0 on the road. For a specific location x ($x > 0$), the number of potential vehicles at this location is related to the ratio of x to security distance SD , and the number of lanes LN . The number of all the potential vehicles at the location x needs to be considered, since each potential vehicle could be the n th following vehicle.

Maximum Number of Potential Vehicles at a Specific Location x The calculation of potential vehicles is also implemented from two standpoints, i.e., the same lane and a different lane from the reference vehicle.

In the same lane as the reference vehicle, there is no vehicle within the range of SD from 0. The distance from the adjacent vehicle to the reference vehicle is equal to or greater than SD . For the same reason, the possible location of the 2nd following vehicle to the reference vehicle starts from $2SD$, and so on. Therefore, the maximum number of potential vehicles in the same lane as the reference vehicle, N_{sl} is

$$N_{sl} = \lfloor \frac{x}{SD} \rfloor \quad (4.44)$$

In a different lane, which is free from the security distance of the reference vehicle, the location of the 1st following vehicle starts from 0. The location of the 2nd vehicle in this lane is greater than SD , and so on. Therefore, the maximum number of potential vehicles in a different lane to the reference vehicle, N_{dl} , is

$$N_{dl} = \lfloor \frac{x}{SD} \rfloor + 1 \quad (4.45)$$

Therefore the maximum total number of potential vehicles N_t at a specific location x is

$$N_t(x) = N_{dl}(x)(LN - 1) + N_{sl}(x) \quad (4.46)$$

where LN is the number of lanes.

Probability of a Specific Vehicle as the n th Following Vehicle at the Location x At x , there are N_t potential vehicles. Any of these vehicles can be the n th following vehicle, since the PDF of any of these vehicles at x is non-zero, but with various probabilities. For a specific vehicle j , the CDF of its location is $F_j(x)$, $j = 1, \dots, N_t$. Note that vehicle j can either be in the same lane as the reference vehicle or in a different lane, and the lane of vehicle j is neglected here. Assume that vehicle j is the n th following vehicle after the reference vehicle, with $n - 1$ vehicles being ahead of vehicle j and others following it. Take the case of $N_t = 7$ and $n = 3$ for example, as is shown in figures 4.16, 4.17 and 4.18. The scenario where vehicle j is the n th following contains several cases, i.e., the vehicles ahead could be vehicles x_1 and x_2 , as is shown in figure 4.16 (combination 1), or vehicles x_2 and x_4 in figure 4.17 (combination 2), vehicles x_1 and x_4 in figure 4.18 (combination 3), and so on. The probability of each combination is determined by the location distribution of all N_t vehicles. Taking combination 1 as an example, the probability that the location of vehicles x_1 and x_2 is less than x is $F_{x_1}(x)$ and $F_{x_2}(x)$. The probability that the location of vehicle x_3 , x_4 , x_5 and x_6 are greater than x is $1 - F_{x_3}(x)$, $1 - F_{x_4}(x)$, $1 - F_{x_5}(x)$ and $1 - F_{x_6}(x)$, where $F_i(x)$ is the CDF of the location of vehicle i relative to the reference vehicle.

According to the property of non-identically-distributed variables in order statistics [61], the probability of vehicle j as the n th vehicle at location x in combination 1 is

$$Pr'_j(x, 1) = \left(\prod_{i=x_1, x_2} F_i(x) \right) f_j(x) \left(\prod_{k=x_3, \dots, x_6} (1 - F_k(x)) \right) \quad (4.47)$$

The probability of vehicle j as the n th vehicle at location x in combination 2 is

$$Pr'_j(x, 2) = \left(\prod_{i=x_2, x_4} F_i(x) \right) f_j(x) \left(\prod_{k=x_1, x_3, x_5, x_6} (1 - F_k(x)) \right) \quad (4.48)$$

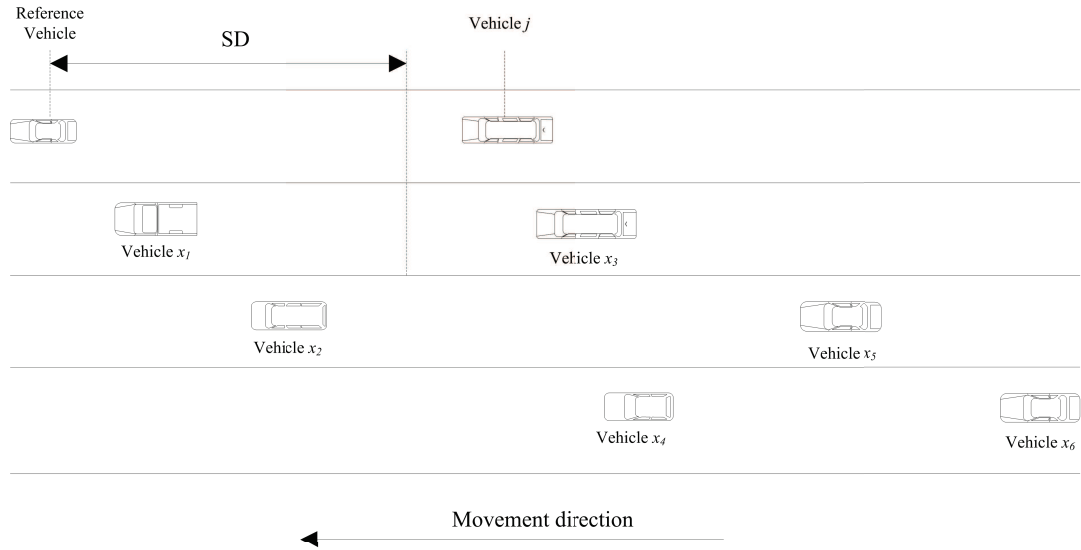


Figure 4.16: Illustration of vehicle j as the n th vehicle, combination 1

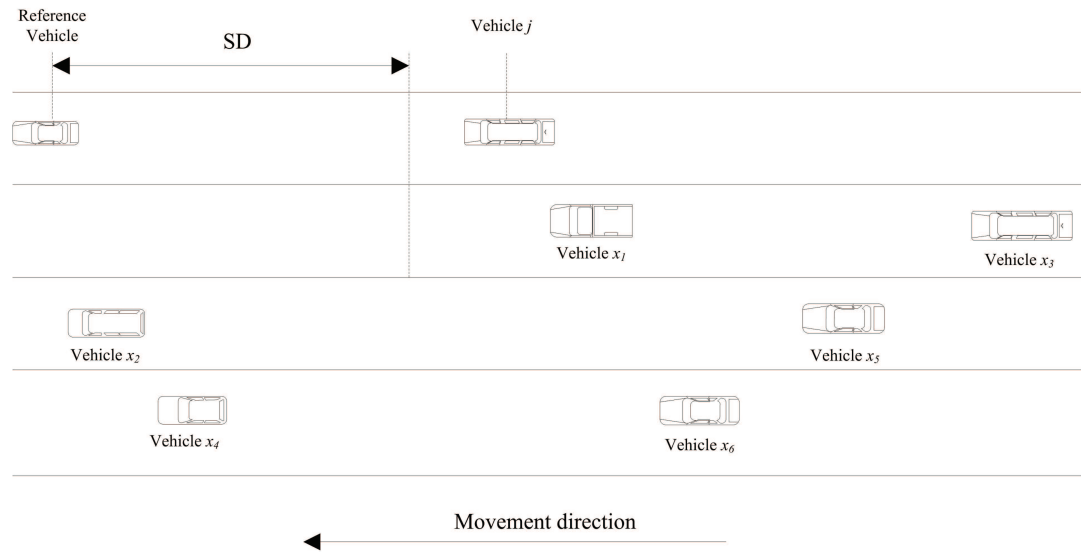


Figure 4.17: Illustration of vehicle j as the n th vehicle, combination 2

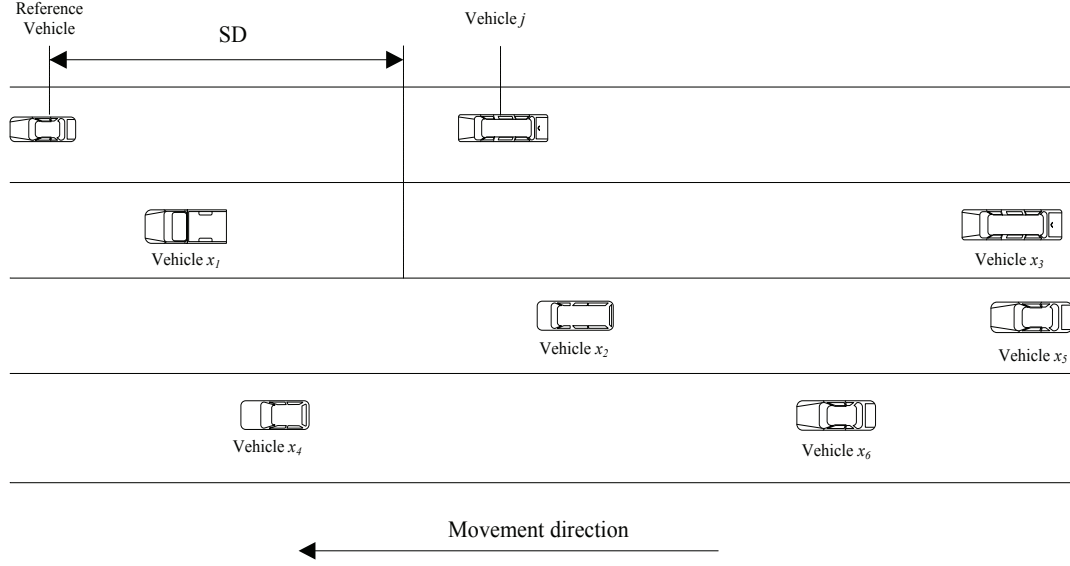


Figure 4.18: Illustration of vehicle j as the n th vehicle, combination 3

The probability of vehicle j as the n th vehicle at location x in combination 3 is

$$Pr'_j(x, 3) = \left(\prod_{i=x_1, x_4} F_i(x) \right) f_j(x) \left(\prod_{k=x_2, x_3, x_5, x_6} (1 - F_k(x)) \right) \quad (4.49)$$

The probability in all the other combinations can also be expressed in the same way.

To make Equations 4.47, 4.48 and 4.49 general, the probability of vehicle j as the n th following vehicle at location x is written,

$$Pr'_j(x) = \left(\prod_{a_i=1}^{n-1} F_{a_i}(x) \right) f_j(x) \left(\prod_{f_i=n+1}^{N_t} (1 - F_{f_i}(x)) \right) \quad (4.50)$$

where $F_a(x)$ and $F_f(x)$ represent the CDF of the vehicles ahead and the following vehicle j , respectively.

The probability that vehicle j is the n th vehicle in all combinations can be written as

$$Pr_j(x) = \sum_{AllCombinations} Pr'_j(x) \quad (4.51)$$

Since every vehicle among N_t vehicles can be the n th following vehicle, the location PDF of

the n th following vehicle is

$$PDF_n = \sum_{j=1}^{N_t} Pr_j \quad (4.52)$$

Issues of the Combinations In Equation 4.51, all the combinations are considered. Some combinations, however, are unrealistic. For example, it is impossible for a vehicle with a greater index in the same lane as vehicle j to become the vehicle ahead and these unrealistic combinations lead to deviations in the results. Here are the principles for excluding unrealistic combinations:

1. The vehicles with smaller indices than vehicle j , and in the same lane, are always the vehicles ahead of vehicle j , the n th following vehicle. If the number of vehicles ahead of vehicle j in the same lane is greater than number n , it is impossible that vehicle j is the n th following vehicle and the probability of this combination is 0;
2. The indices of the vehicles ahead in a different lane from vehicle j are always consecutive and start from 1; otherwise, the possibility of this combination is 0. For example, assume that there are three vehicles in a different lane, say lane K , among the vehicles ahead of vehicle j . The three vehicles can only be the 1st, 2nd, and 3rd vehicles in lane K . The combinations with no consecutive indices, e.g. 1st, 2nd and 4th, and so on are unrealistic and the probability of these combinations is 0.

After excluding all combinations fulfilling the above principles, the remaining combinations are realistic and practical.

4.4.2.4 Selection of Parameter ρ

In the exponential distribution which describes the inter-vehicle space, the parameter ρ is obtained directly from the density. Yet, in the proposed distribution, the security distance has to be incorporated into ρ , since the minimum distance gap between adjacent vehicles in the same lane is the security distance instead of 0 in the exponential distribution.

The parameter ρ represents the number of vehicles in the unit distance, i.e. vehicles per meter in this thesis. ρ in exponential distribution is

$$\rho_{exp} = \frac{VD}{1000} \quad (4.53)$$

where VD indicates the vehicle density, i.e. vehicles per kilometre.

In the proposed distribution, a security distance is guaranteed between adjacent vehicles. In other words, if the security distance is eliminated from the interval of each pair of adjacent vehicles, the vehicles locations follow a strict exponential distribution. Therefore, ρ in the proposed distribution is

$$\rho = \frac{VD}{1000 - VD \cdot SD} \quad (4.54)$$

where SD is the security distance which relates to the vehicle density.

4.4.3 Results and Comparison

The results here present the CDF of vehicles' location in the same lane and different lanes to the reference vehicle at a density of 60 veh per km and 4 lanes. The security distance at this density is 50 metres. The results of the EDSL are compared with the results of an Erlang distribution.

The distance distribution of the n th following vehicle to the reference vehicle follows an Erlang distribution, which is equivalent to cases where 1) the location of vehicles follows a Poisson distribution, and 2) the inter-vehicle space follows an exponential distribution.

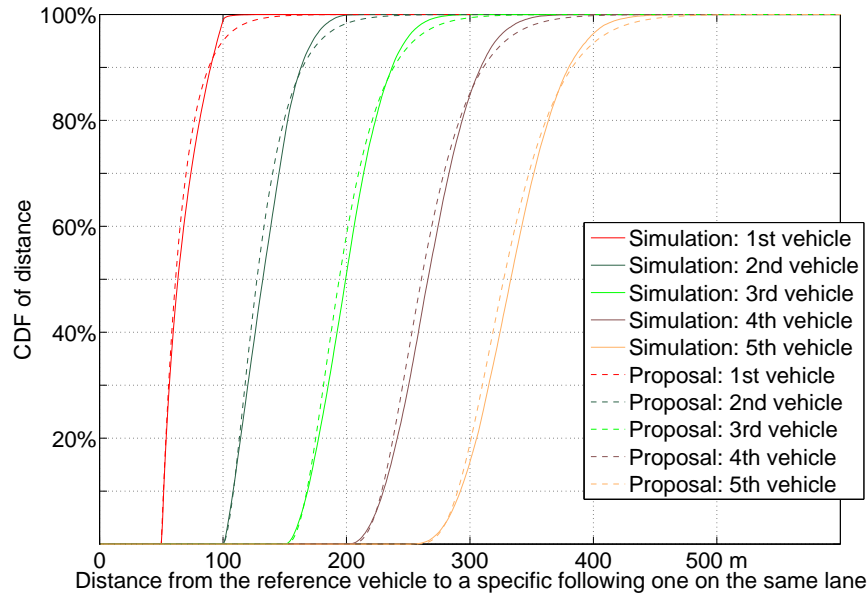


Figure 4.19: The CDF comparison of the following vehicles in the same lane as the reference vehicle, density 15 per km per lane

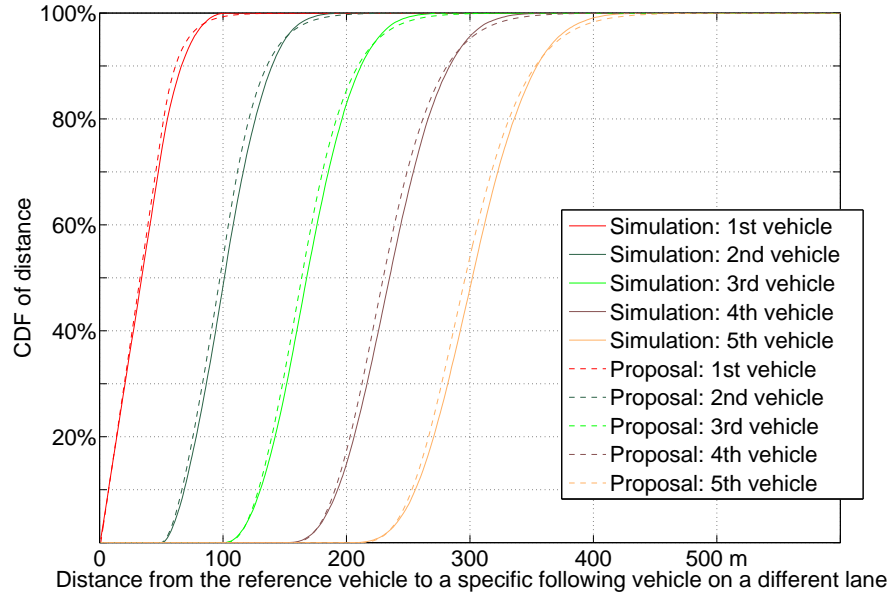


Figure 4.20: *The CDF comparison of the following vehicles in a different lane from the reference vehicle, density 15 per km per lane*

Figures 4.19 and 4.20 present a comparison of the following vehicles in the same lane and in a different lane from the reference vehicle between the simulation results and the numerical results. In both the same lane and different lanes, the numerical results provide an estimation with only up to 10% errors. This is because the security distance is incorporated into the exponential distribution which leads to a more realistic estimation than the exponential distribution.

Figure 4.22 shows that the gap between the proposed distribution and the simulation results rises with the index increasing, yet the distribution still overtakes the Erlang distribution in figure 4.21 in terms of the location range. The inter-vehicle space in the Erlang distribution spreads from 0, which leads to the unrealistic location of the following vehicle. For example, the probability of the 9th following vehicle in the range from 0 to 50 (security distance) is non-zero, which means that there may be 9 vehicles within the range, but this is impossible. In the EDSL, due to the consideration of the security distance, the occurrence of vehicles within this unrealistic range is avoided.

The errors between the numerical results and the simulation in figure 4.22 stem from the dependence on the vehicle location. The PDF of each individual vehicle is a dependent function related to the location of the vehicle ahead due to the existence of the security distance. And

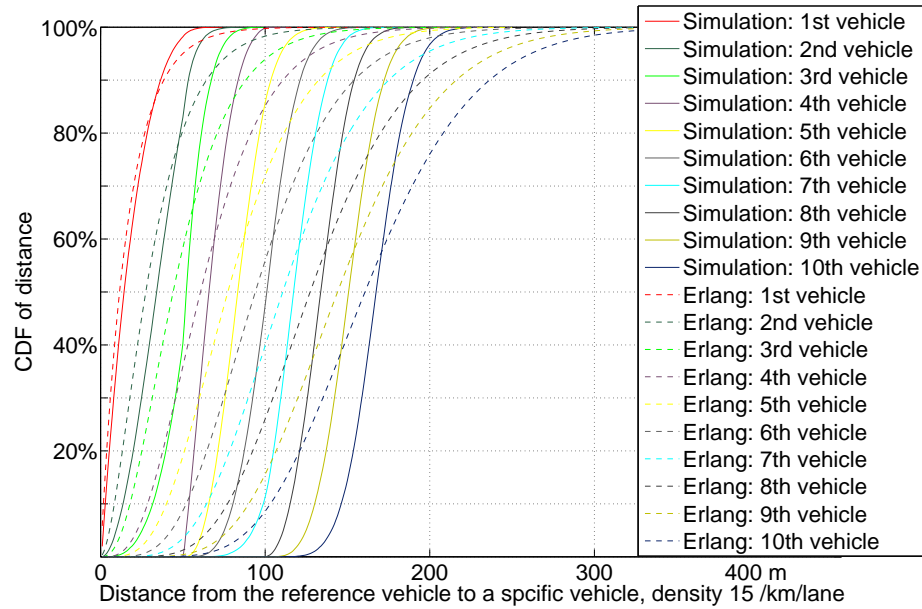


Figure 4.21: The CDF comparison between simulation results and an Erlang distribution, density 15 per km per lane

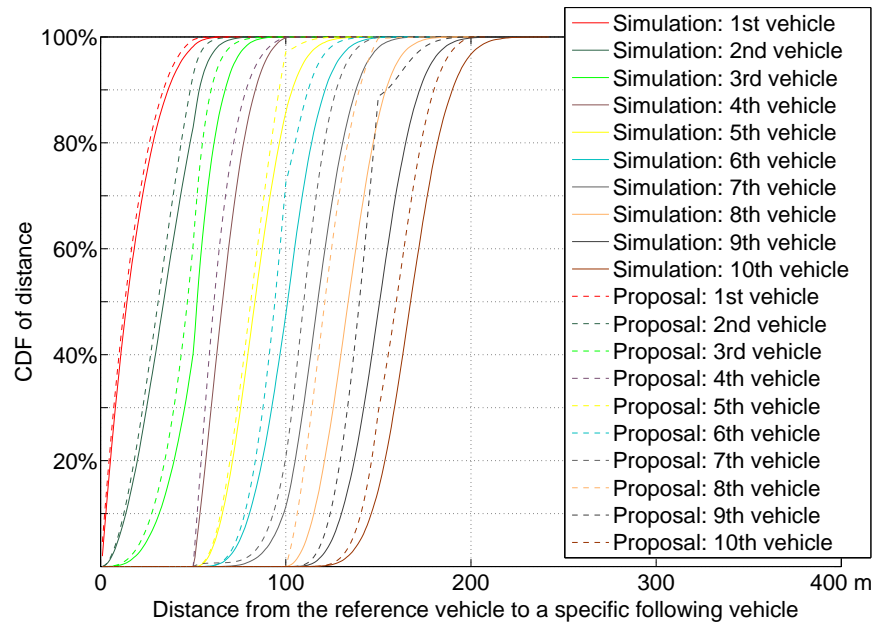


Figure 4.22: The CDF comparison between simulation results and numerical results, density 15 per km per lane

this matches the PDF of the vehicles in the same lane in which the first non-zero value starts from the integral times of the security distance. In the results of the location distribution of the n th following, however, the location of a vehicle makes no impact on the others, since the variables of location are independent in the numerical results; therefore, the security distance between adjacent vehicles in the same lane cannot be guaranteed. For a vehicle i with vehicle $(i - 1)$ ahead, the location of vehicle i is always equal to or greater than the location of vehicle $(i - 1)$ plus a security distance in the simulation. While in the numerical results, vehicle i can be anywhere only if vehicle i is following vehicle $(i - 1)$, since they are independent. The independence of the variables in the numerical results reduces the distance from the reference vehicle to any following vehicle. This accounts for the smaller distance of the numerical results at the same quantile with the simulation results.

4.5 Conclusion

Mathematical models are proposed for both DBA-MAC and the CWCMD to predict and validate the system performance. Simulation and numerical results show that the CWCMD outperforms DBA-MAC in terms of propagation delay and average transmission times in various scenarios. The CW constraint scheme in the CWCMD, which weakens the randomness in CW selection, is the key factor to improve system performance. In addition, the research in this chapter shows that due to the restricting relation between the network formation time and propagation delay, the configuration for optimal system performance, in terms of the DEFT, can be found by adjusting CW related parameters.

In addition, it is often assumed that all the vehicles on the highway follow a Poisson distribution even for vehicles in the same lane. In practice, a security distance has to be guaranteed between adjacent vehicles in the same lane. In this chapter, the proposed distribution EDSL which considers the security distance between adjacent vehicles in the same lane provides a more practical method for modelling traffic.

Chapter 5

Impact of Obstacles on Network Connectivity and System Performance

5.1 Introduction

A significant body of existing literature assumes the signal transmission in VANETs is ideal, i.e. the vehicles within the radio range of the transmitter are able to receive the signal successfully. All the factors which affect communication have been ignored. Experiments [53, 54] have shown that vehicles on the road interfere with the communication, e.g. weaken the signal strength from the transmitter, which leads to the condition that the vehicles are unable to receive the signal from the transmitter even if it is within the radio range.

To show the impact of vehicles between the transmitter and the receiver on signal propagation, network connectivity is studied in this chapter with consideration of obstacles. System performance of different propagation schemes is presented and analysed.

The chapter is organised as follows. Section 5.2 presents existing work concerning obstacles on signal propagation in VANETs. The impact of vehicles as obstacles on network connectivity is analysed in section 5.3. Section 5.4 explores the effect of obstacles on system performance and the necessity to consider them. In section 5.5, an improved scheme of protocol, in which the heights of vehicles are considered, is proposed. Section 5.6 concludes this chapter.

The contributions in this chapter are, 1) analysis of network connectivity with consideration of obstacles and 2) analysis of the impact of obstacles on system performance for different propagation schemes, and 3) the effect of height consideration in the BM selection on propagation performance.

5.2 Obstacle Effects and Signal Attenuation in VANETs

In the network simulation of VANETs it is commonly assumed the vehicles within the radio range of the Tx are able to receive the signal equally. Some factors are ignored in this assumption, such as roadside buildings, trees, vehicles in between the transmitter (Tx) and the receiver (Rx), and the terrain, which causes reflection, diffraction and scattering. Superposition of signals may lead to signal fading due to phase shifts. Accordingly, vehicles within the radio range of the Tx may fail to receive the signal.

Highway road tests were conducted [32, 33] at frequencies of 2.45 GHz and 5.2 GHz. Measurements [32] on an expressway section with nearby office buildings were conducted on two vehicles travelling in the same direction at 2.45 GHz to extract the characteristics and parameters of a vehicular channel. The experiments [33] on the highway with factory buildings near the road are described and the experimental vehicles travelled in the opposite direction to obtain the channel parameters by transmitting testing frames periodically. In both experiments, the impact of the environment on signal propagation stems from the roadside buildings, i.e. office and factory buildings, and the vehicles on the road. The Power-Delay Profile (PDP) results show that the signal power received from the Line-of-sight (LOS) is higher than the reflected signal from roadside buildings by 15 dB-20 dB and the power of other multipath signals is even smaller than from roadside buildings by at least 20 dB. Both experiments indicate that the signal from the LOS is the predominant component in the signal power received.

Furthermore, experiments [53, 54] show that the signal strength received is significantly attenuated at the Rx, due to the vehicles in between the Tx and Rx which block the LOS, and vehicles may fail to receive the signal even if they are within the radio range of the Tx. The remainder of this section summarises the features of the experiments [53, 54]. In the analysis, the vehicle height is categorised into two groups, i.e. low and tall vehicles. The height of each group follows a normal distribution. The antenna is mounted in the middle of the top of the vehicle. The model is a simplified geometry-based deterministic model.

5.2.1 Probability of Vehicles as Obstacles on LOS

The vehicles in between the Tx and Rx are the only factor considered in the analysis and other obstacles, e.g. roadside objects and overpasses, are ignored. The LOS is blocked if any part of any vehicle in between the Tx and Rx lies in the Fresnel zone of the LOS. The Fresnel zone

is the concentric ellipsoid defining the volumes of antenna aperture, which comes from the diffraction of the antenna. Objects in the Fresnel zone lead to the signal attenuation. The radius of the Fresnel zone is

$$r_{nf} = \sqrt{\frac{n_f \lambda_p d_{obs1} d_{TR}}{d_{TR}}} \quad (5.1)$$

where r_{nf} represents the radius of the n th Fresnel zone. The radius of the first Fresnel zone is used to judge whether the vehicles are blocking the LOS path. In this thesis $r_f = r_{1f}$. n_f is the index of the Fresnel zone. For example, for the first Fresnel zone $n_f = 1$, and so on. λ_p indicates the wavelength of the frequency used by Dedicated Short-Range Communication (DSRC), d_{obs1} and d_{TR} are the distance from the Tx to the potential obstacle and from the Tx to the Rx. The major axis is the line through the Tx and Rx. If the obstacle is in the first Fresnel zone, it is blocking the LOS path.

Experiments [62] show that the signal attenuation is negligible if no obstacle exists within 0.6 times the radius of the first Fresnel zone. A vehicle in between the Tx and Rx but outside 0.6 times the radius of the first Fresnel zone is not an obstacle. The relative height of the potential obstacle is

$$h = (h_{Rx} - h_{Tx}) \frac{d_{obs1}}{d_{TR}} + h_{Tx} - 0.6r_f \quad (5.2)$$

where h_{Rx} and h_{Tx} are the height of the Rx and Tx respectively, r_f indicates the radius of the first Fresnel zone. h is the height of the line joining the Tx and Rx at the location of the potential obstacle. The probability of one vehicle blocking a LOS between the Tx and Rx $P(LOS|h_{Tx}, h_{Rx})$, is

$$P(LOS|h_{Tx}, h_{Rx}) = 1 - Q\left(\frac{h - \mu}{\sigma}\right) \quad (5.3)$$

where $Q(\cdot)$ is the Q -function, and μ and σ are the mean and standard deviation of the height h , respectively. Moreover, if there are N_0 vehicles between the Tx and Rx, the probability that the LOS path is not blocked is [62]

$$P(n, LOS|h_{Tx}, h_{Rx}) = \prod_{k=1}^{N_0} \left[1 - Q\left(\frac{h_k - \mu_k}{\sigma_k}\right) \right] \quad (5.4)$$

where h_k is the height of the k th potential obstacle, and μ_k and σ_k are the mean and standard deviation of the height of the k th potential obstacle.

5.2.2 Effect of Vehicle as Obstacle on Signal Propagation

To quantify the attenuation by the obstacles, diffraction models in ITU-R recommendation [63] are adopted. The size of the obstacles, i.e. vehicles, is much greater than the wavelength, which is the requirement to apply diffraction models.

The simplest case is that there is only one vehicle as the obstacle and the single knife-edge model can be applied to this case. In a single knife-edge model, the obstacle is regarded as a half plane, which simplifies the calculation. In the case of multiple obstacles, a multiple knife-edge model [63], i.e. Epstein-Paterson model, is adopted in the analysis, which provides an optimistic approximation of signal attenuation. Notice in the latest recommendation of diffraction models [63], the Epstein-Paterson model is replaced by the Bullington model which provides reliable results for diffraction for various paths, regardless of terrain. In the research of this thesis, diffraction models [63] are adopted. Free space path loss (FSPL) is used to define the effect of vehicle separation [64].

Experiments were carried out [53, 54] to test the obstacle effect in a variety of scenarios, e.g. static conditions in a parking lot, movement on a highway, and in a suburban and an urban canyon. The Tx and Rx were cars and the obstacle vehicle was a van. Experimental results indicate that the performance in terms of Packet Delivery Ratio (PDR) and Received Signal Strength Indicator (RSSI) are significantly affected by the presence of the obstacle. The RSSI is reduced from 7 dB to 20 dB approximately when the distance between the Tx and Rx is not greater than 100 metres. The PDR drops significantly as the distance between the Tx and Rx increases.

5.2.3 Effect of Obstacle Height on Signal Propagation

M. Boban et al. carried out research on the effects of obstacle height on signal propagation [34]. Experimental results show that the system performs better in terms of the PDR where at least one of the Tx or Rx is a tall vehicle, e.g., van. This is because once tall vehicles are used to forward messages they are less likely to be obstructed than short vehicles.

The performance of packet delivery is improved by using tall vehicles as relays [34]. When considering latency, the number of times a message is transmitted by the relays and the distance between relays have to be considered. Therefore, balancing the effect of the height and location of the potential relays in the selection procedure of relays could be an interesting topic for

further research.

5.3 Obstacle Effect to Network Connectivity

5.3.1 Estimation Models of Signal Strength

The diffraction models recommended by the ITU are adopted here to estimate the attenuation by obstacles.

To deal with the case of a single obstacle between the Tx and Rx, the single knife-edge model is adopted. Attenuation by a single obstacle A_{sk} is

$$A_{sk} = \left[6.9 + 20 \log_{10} \left(\sqrt{(V - 0.1)^2 + 1} + V - 0.1 \right) \right] H(V + 0.1) \quad (5.5)$$

$$V = \Delta h \sqrt{\frac{2}{\lambda_p} \left(\frac{1}{d_{TTO}} + \frac{1}{d_{TOR}} \right)} \quad (5.6)$$

where Δh is the gap between the height of the obstacle and the LOS path at the location of the obstacle. If the height of the obstacle is above the line connecting the Tx and Rx, $\Delta h > 0$; otherwise, $\Delta h < 0$. d_{TTO} and d_{TOR} represent the distance from the Tx to the Top of the Obstacle and from the Top of the Obstacle to the Rx. An illustration of the parameters is shown in Figure 5.1 [63].

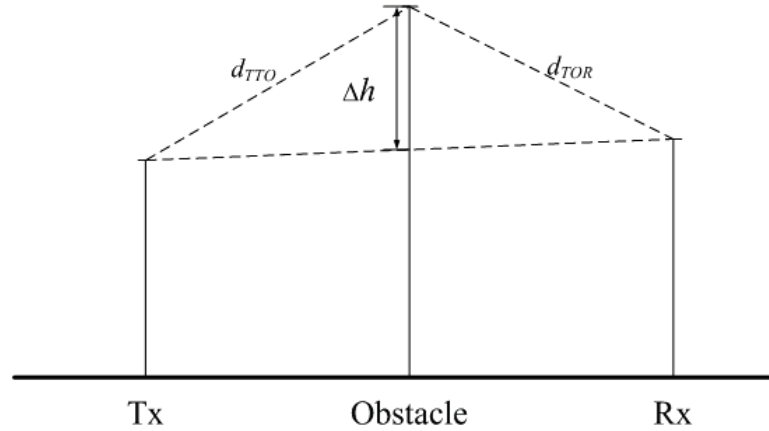


Figure 5.1: Illustration of single knife edge

The double-isolated-edges model is adopted in the case of two obstacles between the Tx and Rx. This model applies the single knife-edge model twice successively with obstacles 1 and 2 being regarded as the Rx and Tx in turn. In the first step, obstacle 2 is regarded as the Rx, and the attenuation is caused by obstacle o1. Then, obstacle 1 is the Tx and obstacle 2 is the source of signal attenuation. The model is illustrated in Figure 5.2 [63].

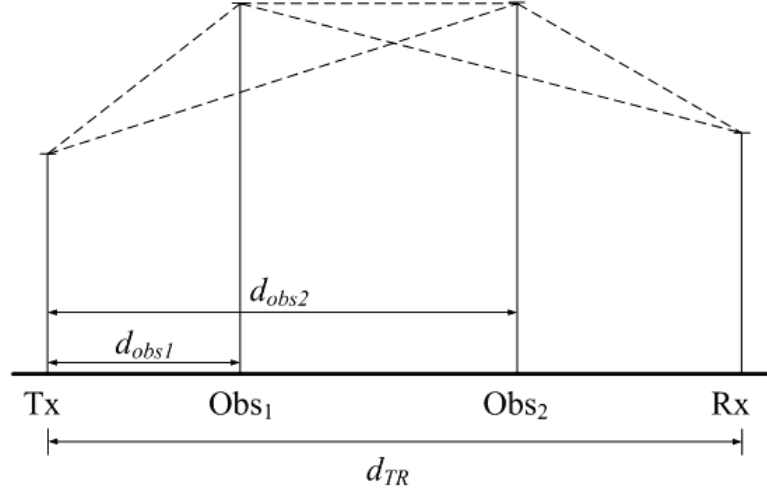


Figure 5.2: Illustration of double isolated edges

Attenuation by two obstacles is given by

$$A_{di} = A_{sk1} + A_{sk2} + A_c \quad (5.7)$$

where A_{sk1} and A_{sk2} are the attenuation by obstacle 1 and 2. A_{sk1} and A_{sk2} can be derived from the single knife-edge model. A_c is the correction term, which is estimated by Equation 5.8

$$A_c = 10 \log_{10} \left[\frac{d_{obs2} (d_{TR} - d_{obs1})}{(d_{obs2} - d_{obs1}) d_{TR}} \right] \quad (5.8)$$

where d_{obs1} and d_{obs2} are the distance from the Tx to the first obstacle and from the Tx to the second obstacle. d_{TR} is the distance between the Tx and Rx.

For the case of three obstacles and more, the Bullington model is adopted. An equivalent obstacle is used to replace multiple obstacles. To get the equivalent obstacle, join Tx and the obstacles and keep the line with the largest elevation angle so that all the vehicles touch or are below the line. The same procedure is carried out on Rx and another line is derived. The

location and height of the equivalent obstacle are determined by the intersection of the two lines or their extension, as is shown in Figure 5.3 [63].

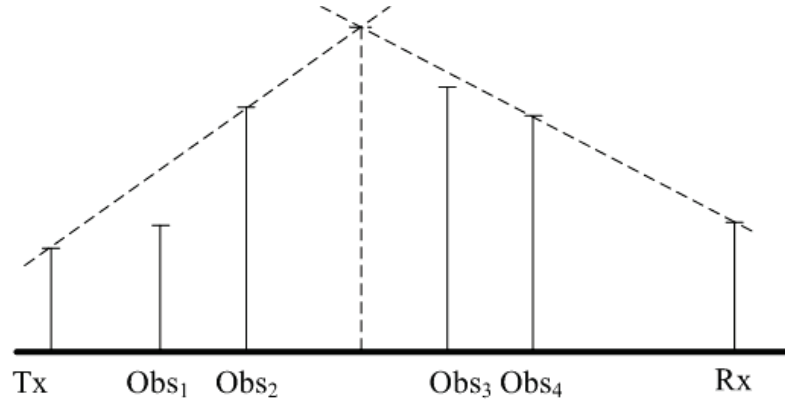


Figure 5.3: *Illustration of Bullington method*

The above models are used to estimate the attenuation by obstacles. The FSPL is adopted for the strength loss due to the distance between the Tx and Rx. The expression is

$$A_{fs} = 10 \log_{10} \left(\left(\frac{4\pi}{c_l} d_{TR} f_p \right)^2 \right) \quad (5.9)$$

where c_l is the speed of light, 3×10^8 m/s, f_p is the carrier frequency of the DSRC, 5.9 GHz. In the case of the LOS, path loss is the only source of signal reduction and the radio range is determined by path loss.

5.3.2 Network Connectivity

To indicate the effect of vehicles as obstacles on signal strength, network connectivity on the road is presented here. The simulations show instantaneous results. Yet, due to the statistical property of the vehicle location, they are also applicable to the connection condition of the network at any instant. In addition, how the obstacles affect system performance is also presented in the later parts of this chapter.

5.3.2.1 Methodology

The mobility model is the same as the one in Chapter 3. The speed is used to predict the location of vehicles at the end of the period and to determine the suitability of candidates as BM.

The vehicles are distributed on the road randomly except that the distance between consecutive vehicles in the same lane is not less than the predefined security distance. In addition, the height of the vehicles is incorporated to reflect the practical case more accurately. The vehicles are categorized into tall and low types, that is, a vehicle is either a tall vehicle or a low vehicle.

In the diffraction models [63], if the length of the obstacle is far greater than the wavelength, the obstacle blocking LOS can be treated as an edge with only height in the dimensions being considered during the calculation. That is, the attenuation caused by the body of the obstacle is the one caused by the edge only; therefore the vehicles in the simulation are interpreted as edges which are of the width of the lane. The height of the vehicles is adopted to calculate the attenuation.

Notice that, in the signal propagation, the LOS is considered to be the only component in the received signal. Any NLOS signal, e.g. reflection and scattering, is neglected, as it is not the predominant part of the signal received [32, 33].

In the simulation, the transmitter broadcasts a message. The transmitter and the selected receiver are connected by a Light-of-Sight (LOS) path. The vehicles intersecting with the LOS are the obstacles and they are involved in the attenuation calculation from the diffraction models.

If the signal strength received is above the threshold of the sensor, the link between the transmitter and the receiver is connected; otherwise, it is disconnected. The network connectivity is for the direct communication between any pair of vehicles within the mutual transmission range. Communication with a vehicle outside the transmission range is via intermediate nodes and is excluded from this work.

A Monte Carlo simulation is conducted to get the statistical results. In each iteration, once the vehicles are located on the ring-shaped 8-km road model, a random one is selected as the transmitter. Among the following vehicles within the transmission range, a receiver is randomly selected as well. The vehicles blocking the LOS of the transmitter and the receiver are the obstacles. The simulation is repeated 100,000 times in order to get a reliable result.

5.3.2.2 Configuration

The simulations are carried out in three densities, i.e. 20, 60 and 100 veh per km. The vehicle height is categorised into two groups, i.e. tall and low vehicles. For each group, the height follows a normal distribution [34]. The configuration of traffic parameters are the same as those in Chapters 3 and 4. The transmission-related parameters are listed in Table 5.1

P_{Tx}	16 dBm
Th_{Rx}	-79.5 dBm
f_p	5.9 GHz
C_l	3×10^8 m/s

Table 5.1: Configuration of transmission

Th_{Rx} represents the threshold of Rx, which is above the minimum sensitivity (-80 dBm) of the DSRC in the QPSK model [53]. Based on the configuration, the maximum transmission range is 240 m.

Table 5.2 presents the height of short and tall vehicles [34]. In the following results, the con-

Height of tall vehicles: mean	3.35 m
Height of tall vehicles: standard deviation	0.08 m
Height of short vehicles: mean	1.5 m
Height of short vehicles: standard deviation	0.08 m

Table 5.2: Configuration of vehicles' height

nectivity probability in various ratios of tall vehicles are presented.

5.3.2.3 Simulation Results of Connectivity Probability at a fixed Ratio of Tall Vehicles

The results in this section present the impact of the vehicle density and the distance on connectivity probability. The ratio of tall vehicles is set to 0.1.

Figure 5.4 shows that the connectivity probability reduces with the increase of distance, as expected. With the distance between Tx and Rx increasing, there are more vehicles as well as obstacles, which accounts for the decreasing connectivity probability. It is seen that as the distance increases, the connectivity probability is higher at a density of 20 than at a density of 100. This is because at a lower density the same distance, e.g. 100 metres, is occupied by fewer

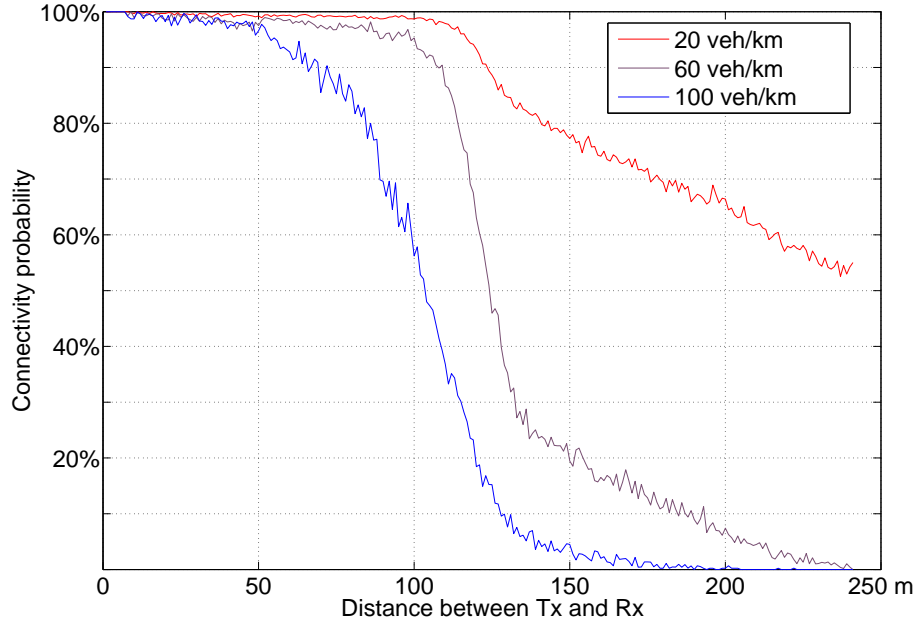


Figure 5.4: Connectivity probability in all densities

vehicles as well as obstacles. The signal strength is weakened by obstacles less significantly at a low density. The relation between the distance of the Tx and Rx and the maximum number of obstacles in between is presented in the next section.

The absolute gap between the lanes of the Tx and Rx is defined as ΔLN . There are three cases of lane relation between Tx and Rx, 1) in the same lane, $\Delta LN = 0$, 2) in an adjacent lane, $\Delta LN = 1$ and 3) at least one lane apart $\Delta LN > 1$. The distance between Tx and Rx, d_{TR} , is expressed as the multiple of the security distance and the ceiling of the distance is adopted in the analysis. For example, if $d_{TR} = 1.3SD$, then in the results $d_{TR} < 2SD$. Results of individual cases are presented in Table 5.3.

Based on the above results, a general procedure for determining the number of obstacles is given here:

Assume the distance between the Tx and Rx d_{TR} satisfies $(k-1)SD \leq d_{TR} < kSD$ and the gap of lanes in between the Tx and Rx $\Delta LN = n$. $n \geq 1$ where the two vehicles being considered are not in the same lane and $\Delta LN = 0$ for the case of the two being in the same lane. Two cases are considered here, the obstacles in a different lane from the Tx/Rx and the obstacles in the same lane as the Tx/Rx.

d_{TR}	max. obs # $\Delta LN = 0$	max. obs # $\Delta LN = 1$	max. obs # $\Delta LN = 2$	max. obs # $\Delta LN = 3$
$<SD$	0	0	1	2
$<2SD$	0	0	1	2
$<3SD$	1	2	2	2
$<4SD$	2	2	2	4
$<5SD$	3	4	5	4
$<6SD$	4	4	5	4
$<7SD$	5	6	6	8
$<8SD$	6	6	6	8
$<9SD$	7	8	9	8
$<10SD$	8	8	9	10
$<11SD$	9	10	10	10
$<12SD$	10	10	10	10

Table 5.3: Relation between maximum obstacle number and d_{TR}

The length of the LOS on the lane of the Tx and Rx is less than $\frac{k}{2n}SD$, since the minimum distance between vehicles in the same lane is SD . By rounding up $\frac{k}{2n}$ the maximum number of vehicles in the lane of the Tx/Rx, which includes the Tx/Rx themselves, may be determined. Therefore, the maximum number of the obstacles in the lanes of the Tx and Rx is $2 \left(\left\lceil \frac{k}{2n} \right\rceil - 1 \right)$.

Regarding the obstacles in the lanes without the Tx/Rx ($n > 1$), the length of the LOS on the lane is less than $\frac{k}{n}SD$. As with the case of the lane(s) of the Tx and Rx, the rounding up of $\frac{k}{n}$ determines the maximum number of vehicles in LOS in one lane between the Tx and Rx. In total, there are $n - 1$ lanes, excluding the Tx or Rx. The maximum number of obstacles in the lanes without the Tx or Rx is $\left\lceil \frac{k}{n} \right\rceil (n - 1)$.

For the case where the Tx and Rx are in the same lane, the number of obstacles cannot exceed $(k - 2)$. Thus, the maximum number of obstacles for the case where the Tx and Rx are in the same lane is $(k - 2)H(k - 2)$.

For all three cases of the lane relation between the Tx and Rx, i.e. Tx/Rx in the same lane, Tx/Rx in adjacent lanes and others, given that d_{TR} , as $0 < d_{TR} < kSD$, $k = 1, 2, 3, \dots$, the maximum number of obstacles can be summarised as follows:

1) Tx and Rx in the same lane, maximum number of obstacles,

$$ON_s = (k - 2)H(k - 2) \quad (5.10)$$

2) Tx and Rx in adjacent lanes, maximum number of obstacles,

$$ON_a = 2 \left(\left\lceil \frac{k}{2} \right\rceil - 1 \right) \quad (5.11)$$

3) Tx in lane one and Rx in lane n , maximum number of obstacles,

$$ON_o = \left\lceil \frac{k}{\Delta LN} \right\rceil (\Delta LN - 1) + 2 \left(\left\lceil \frac{k}{\Delta LN} \frac{1}{2} \right\rceil - 1 \right) \quad (5.12)$$

Summarising the above analysis, we conclude that if $d_{TR} < kSD$ ($k = 1, 2, 3 \dots$), the maximum number of obstacles between the Tx and Rx is $\max(ON_s, ON_a, ON_o)$. With an increase of d_{TR} , or k , the maximum number of obstacles rises which accounts for the reduction of connection probability.

In addition, Figure 5.4 indicates that at the same distance, the connection probability rises with a decrease of vehicle density. At a higher density, more vehicles exist in between the Tx and Rx at a specific distance as well as a higher maximum number of obstacles shown in Table 5.3. Figure 5.5 presents the connectivity with one obstacle and two obstacles.

The above figure presents the connectivity probability with 1 obstacle and 2 obstacles. The results for 1 obstacle show a step-shaped reduction of connection probability between 110 m and 120 m. As d_{TR} is less than 100 metres, the connection probability is approximately constant at 90%. Over this range in the cases where the obstacle is a tall vehicle and at most one of the Tx-Rx pair is a tall vehicle, the attenuation with path loss is large enough to disconnect the Tx and Rx. For example, if $d_{TR} = 50$ m, $h_{Tx} = h_{Rx} = 1.5$ m, $h_{obs} = 3.35$ m and the obstacle is halfway between the Tx and Rx, the attenuation by the obstacle $A_{sk} = 23.17$ dB, and free space path loss $A_{fs} = 81.84$ dB. The signal strength received is $P_{Tx} - A_{sk} - A_{fs} = -89$ dBm, which is lower than the threshold -79.5 dBm.

In the range from 110 m to 120 m, the connection probability experiences a sharp reduction. This is due to the increase of free space path loss. The signal strength at the Rx drops to be lower than the sensitivity of the Rx.

From 120 m to the edge of the maximum radio range, the connection probability stays in the range from 10% to 20%, although the path loss is still increasing. In the cases where the

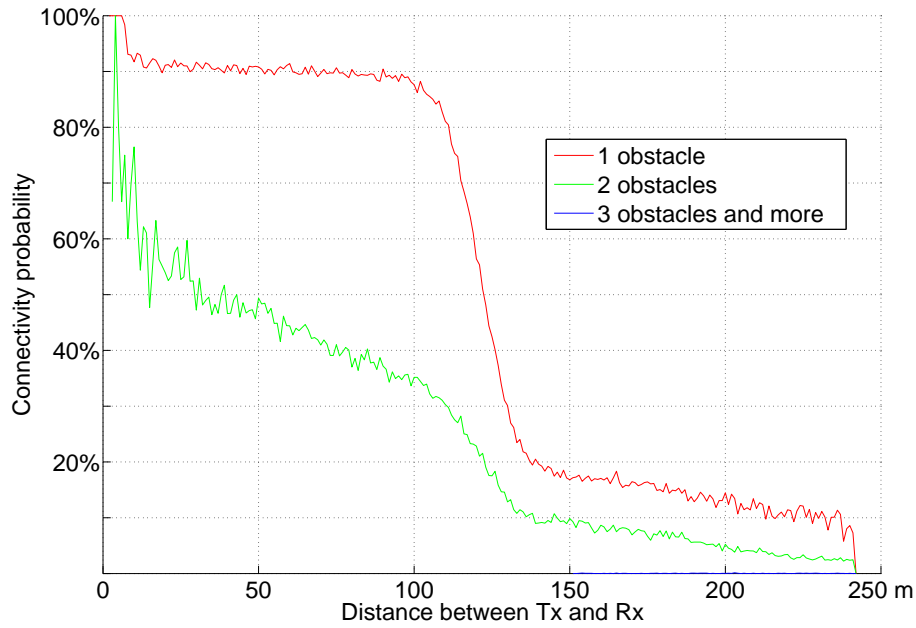


Figure 5.5: Connectivity probability by 1 obstacle, 2 obstacles and more

obstacle is a low one and at least one of the Tx-Rx pair is a tall vehicle, the signal strength received is above the threshold of the Rx. For example, if $d_{TR} = 200$ m, the obstacle is midway between the Tx and Rx, $h_{obs}=1.5$ m, $h_{Tx}=h_{Rx}=3.35$ m, the attenuation is $A_{sk}=0$, with path loss $A_{fs} = 93$ dB. Thus the Rx is able to receive the signal successfully.

In the above results of section 5.4.2, the ratio of tall vehicles is set to 0.1. To indicate the impact of the ratio of tall vehicles on network connection, more results of various ratios of tall vehicles are presented in the following parts.

5.3.2.4 Simulation Results of Connectivity Probability at various Ratio of Tall Vehicles

This section provides the results of connectivity probability at different ratios of tall vehicles to show its impact on connectivity probability. The ratio of tall vehicles examined are 0, 0.05, 0.1 and 0.2. The density of vehicles is set to 60 veh per km.

As is shown in figure 5.6, the radio range can be divided into three intervals based on the connection, i.e. close distance from 0 to about 110 m, middle distance from 110 m to 140 m and far distance from 140 m. The connection at different ratios of tall vehicles share similarities,

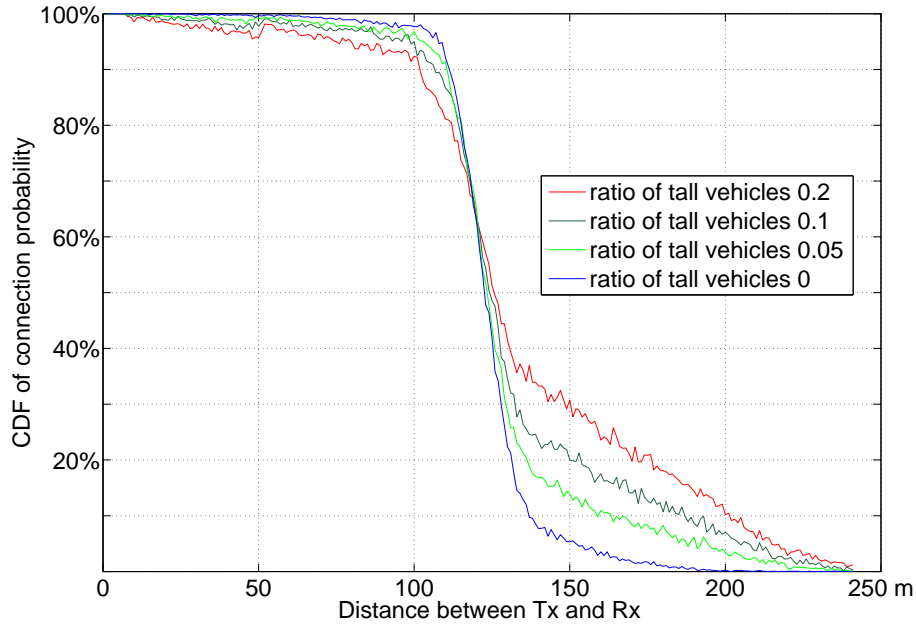


Figure 5.6: Connectivity probability in 4 different ratios of tall vehicles, density 60

i.e. high connection at close distance, sharp drop at middle distance and low connection in far distance.

At a close distance, since the signal loss by distance is relatively small, the main combination of height which affects the signal strength at Rx are the cases where obstacle(s) in between Tx and Rx is (are) taller than Tx and Rx, i.e., tall obstacle(s) and short Tx/Rx. In the combination of tall obstacle(s) and short Tx/Rx, the signal strength is attenuated more significantly than in other combinations as described by the diffraction models. The occurrence of these cases depends on the ratio of tall vehicles. As the ratio is 0.2, the probability of one tall obstacle and short Tx/Rx is 12.8% ($80\% \times 20\% \times 80\%$). In the case of ratios lower than 0.2, the occurrences of these combinations get less frequent and therefore the connection probability is higher in a lower ratio of tall vehicles. A special case is that if the ratio of tall vehicles is 0, all the vehicles are low ones and the attenuation is less than the combinations of tall obstacles and short Tx/Rx, which accounts for the higher connection of a lower ratio of tall vehicles in the figure.

In the middle distance, the rise of path loss results in a drop in signal strength through the threshold of the receivers' sensitivity and disconnects the link of the Tx and potential Rx in the combination of short Tx/Rx and obstacle(s), which is the combination with the biggest ratio.

The connectivity, therefore, drops dramatically.

In the far distance, which is close to the edge of the radio range, due to the more significant path loss, obstacles play a predominant role in the network connection. Since the probability of there being no obstacle is almost zero close to the edge of the radio range, the cases where obstacles cause little attenuation matter, i.e., tall Tx/Rx and short obstacle(s), tall Tx (or Rx) and short Rx (or Tx) and obstacle(s). The total probability of these cases in the ratio of 20% tall vehicles is 28.8% which is greater than the probability of 17.1% in the ratio of 10% and other scenarios. This accounts for the higher connection probability at the distance close to the edge of the radio range for a higher ratio of tall vehicles. In the case of 0 tall vehicles, no matter which combination it is, the obstacle attenuates the signal strength and since the sum of path loss and attenuation is big enough, the link between Tx and Rx disconnects.

5.4 The Effect of Obstacles on the System Performance of Protocols

In this part, the system performance of DBA-MAC and the CWCMD is presented. In the simulation, the effect of obstacles is considered in both BM formation and message transmission. The results are compared with the ideal case in which all the vehicles are able to receive the signal equally in the maximum radio range of the Tx. The configuration in this part is the same as those in the simulation of Chapter 3 and 4.

Density /km	100	60	20
without obstacles	181.92 \pm 59.62	180.21 \pm 58.48	170.41 \pm 57.57
with obstacles	63.10 \pm 33.73	90.44 \pm 49.07	146.53 \pm 61.90

Table 5.4: Average distance between adjacent BMs in DBA-MAC with and without obstacle effect

Density /km	100	60	20
without obstacles	229.05 \pm 7.86	222.97 \pm 12.23	196.00 \pm 35.01
with obstacles	108.14 \pm 24.90	141.50 \pm 38.97	171.49 \pm 46.22

Table 5.5: Average distance between adjacent BMs in the CWCMD with and without obstacle effect

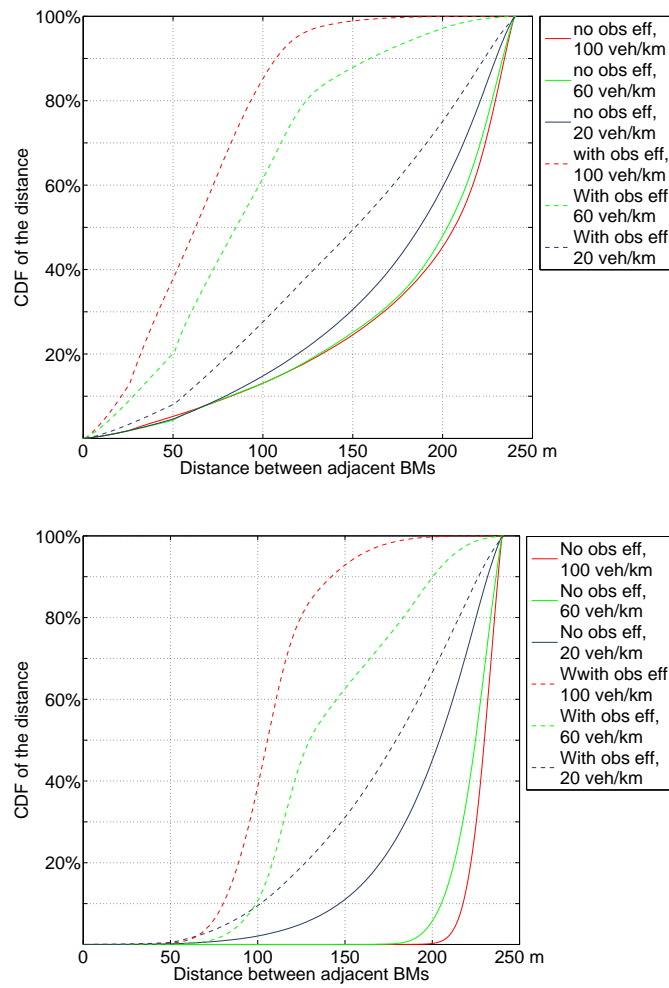


Figure 5.7: Impact of obstacles on the BM selection in DBA-MAC (up) and the CWCMD (down)

Figure 5.7, Table 5.4 and 5.5 present the impact of obstacles on the BM selection in DBA-MAC and the CWCMD. Due to the obstacle effect, the number of suitable candidates reduces and the candidates are excluded from the suitable candidates if the signal strength received is below the threshold of the Rx. Farther candidates are excluded from the set of suitable candidates with higher probability, due to the increasing number of obstacles as indicated in Table 5.3. Therefore, suitable candidates are closer to the BM than in the ideal case.

The selection performance of the CWCMD is better than DBA-MAC, as is shown in Figure 5.7. Due to the property of the CWCMD that the candidate with the highest suitability responds to the BM prior to others, the winning candidate is still the one with the highest suitability among

the decreasing number of suitable candidates. Even in the condition of obstacle effect, the CWCMD still provides better performance of the BM selection than in DBA-MAC.

It is also noted that in the case of obstacles the performance of the BM selection is better at a lower density than at a high density, which is the opposite to the ideal case with no obstacle. If more obstacles exist between the Tx and Rx for a specific distance, the signal strength received is affected more by the obstacles, as is shown in Figure 5.5. The average number of vehicles within a specific range, including obstacles, rises with the increase of vehicle density. This means that the average distance between adjacent BMs at a high density is smaller than the one at a low density when considering the obstacle effect.

The CDFs of the results are plotted in Figure 5.7. Without considering obstacles, as analysed in the last chapter, the suitable candidate farthest from the BM will win the contention with highest probability in both schemes. Thus, at a high density a longer BM distance is achieved on average. However, obstacles affect propagation at a high density more severely than at a low density. Hence, the suitable candidates are closer to the BM at a high density than at a low density.

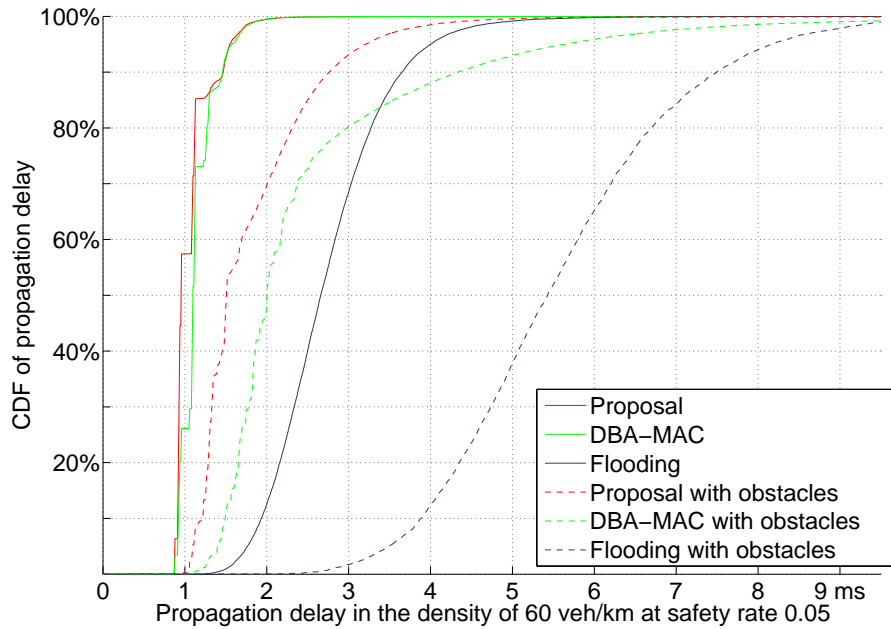


Figure 5.8: The performance comparison with and without obstacles in flooding, DBA-MAC and the CWCMD

	DBA-MAC	CWCMD	Flooding
without obstacle	1.144 ± 0.280	1.070 ± 0.360	2.748 ± 0.712
with obstacle	2.552 ± 2.482	1.821 ± 0.991	5.575 ± 1.443

Table 5.6: Average delay in DBA-MAC, the CWCMD and flooding with and without obstacle effect, /ms

	DBA-MAC	CWCMD	Flooding
without obstacle	6.04 ± 0.84	5.55 ± 0.74	9.57 ± 2.27
with obstacle	10.42 ± 1.85	8.05 ± 1.43	16.32 ± 4.01

Table 5.7: Average retransmission times in DBA-MAC, the CWCMD and flooding with and without obstacle effect

Figure 5.8 shows that the performance delay is significantly affected by the obstacles. The propagation delays in all densities are affected by obstacles. The performance of the CWCMD is still better than the one in DBA-MAC.

Regarding the distance between BMs, the trend of delay performance with respect to the vehicle density is opposite to the results obtained when obstacles are considered. This result matches the performance of the BM selection, as is shown in Figure 5.7. The shift of performance is because the increase of vehicle density brings about more obstacles and the connectivity is increasingly affected.

Figure 5.9, Table 5.9, Table 5.10, Figure 5.10, Table 5.11 and Table 5.12 present the results of delay and retransmission times in both DBA-MAC and the CWCMD in various densities, with and without consideration of obstacles. The results match the one of Figure 5.7, Table 5.4 and 5.5, which indicate that the CWCMD outperforms DBA-MAC in either ideal case without considering obstacles or in the case of considering obstacles. The performance is better at a lower density than at a high density when obstacles are taken into account. This is opposite to

	DBA-MAC	CWCMD	Flooding
without obstacle	180.21 ± 58.48	222.97 ± 12.23	123.52 ± 68.38
with obstacle	90.44 ± 49.07	141.50 ± 38.97	72.58 ± 43.42

Table 5.8: Average distance between adjacent intermediate nodes in DBA-MAC, the CWCMD and flooding with and without obstacle effect, /m

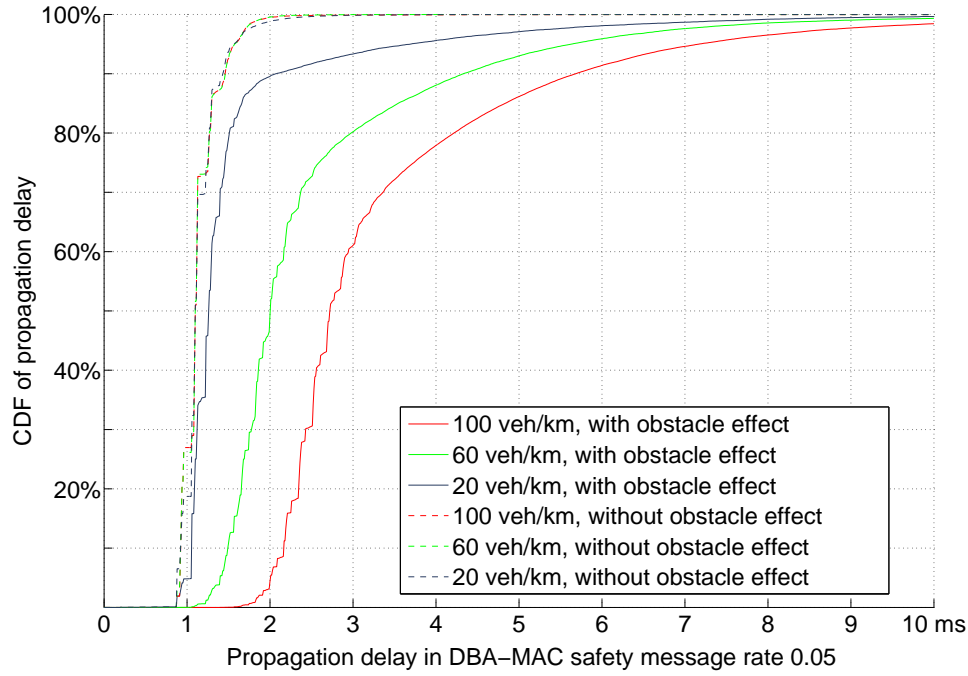


Figure 5.9: The performance comparison with and without obstacles in DBA-MAC at message rate 0.05

Density /km	100	60	20
Without obstacle	1.141 ± 0.473	1.144 ± 0.280	1.156 ± 0.290
With obstacle	3.473 ± 3.004	2.552 ± 2.482	1.581 ± 1.296

Table 5.9: Average delay in DBA-MAC in various densities with and without obstacle effect

Density /km	100	60	20
Without obstacle	6.03 ± 0.83	6.04 ± 0.84	6.15 ± 0.82
With obstacle	14.18 ± 2.02	10.42 ± 1.85	6.94 ± 1.11

Table 5.10: Average retransmission times in DBA-MAC in various densities with and without obstacle effect

Density /km	100	60	20
Without obstacle	1.065 ± 0.390	1.070 ± 0.360	1.096 ± 0.384
With obstacle	2.529 ± 2.508	1.821 ± 0.991	1.272 ± 0.588

Table 5.11: Average delay in the CWCMD in various densities with and without obstacle effect

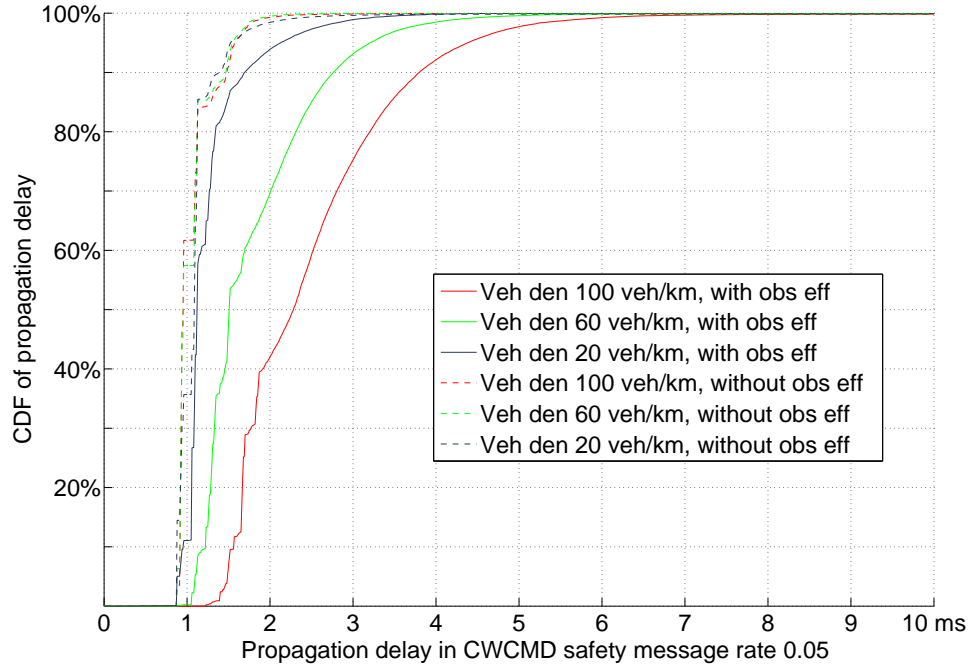


Figure 5.10: The performance comparison with and without obstacles in the CWCMD at message rate 0.05

Density /km	100	60	20
Without obstacle	5.51 ± 0.75	5.55 ± 0.74	5.77 ± 0.73
With obstacle	10.47 ± 1.82	8.05 ± 1.43	6.35 ± 0.87

Table 5.12: Average retransmission times in the CWCMD in various densities with and without obstacle effect

the situation of the ideal case, in which performance at a high density is better.

In the CWCMD, the candidate with the highest suitability is more likely to win the contention to become the next BM than in DBA-MAC, where the candidates of weaker suitability still have the chance to become the next BM. The inclusion of the effect of obstacles does not change the selection mechanism of the CWCMD in which the best candidate responds before all the others. Therefore, the CWCMD still outperforms DBA-MAC when the effect of obstacles is included.

5.4.1 The Effect of Changing Ratio of Tall Vehicles on the System Performance of Protocols

In this section, the effect of the ratio of tall vehicles will be presented in the cases of different ratios of tall vehicles. The ratio of tall vehicles is selected from four possibilities, i.e., 0, 0.05, 0.1 and 0.2. The density of the vehicles is set to 60 veh per km.

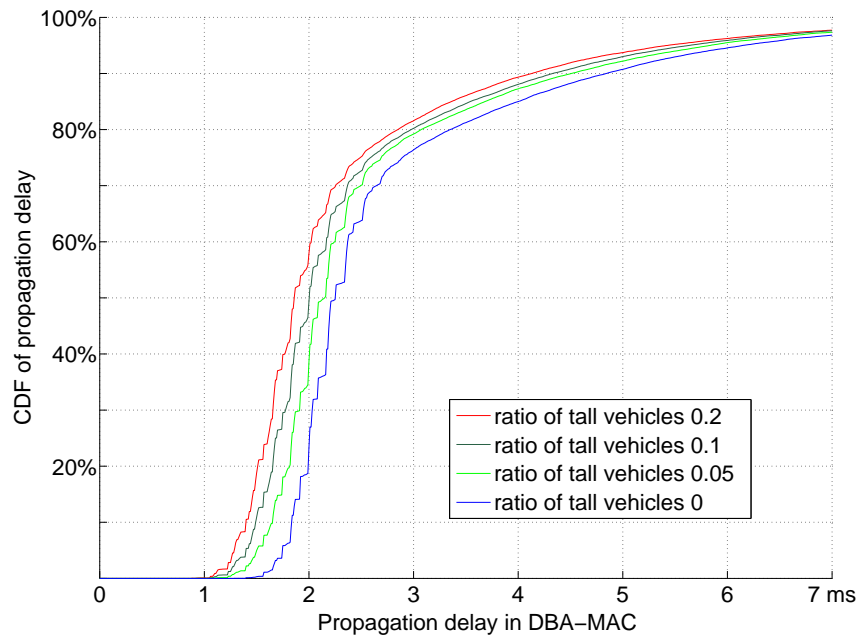


Figure 5.11: *The performance comparison of DBA-MAC at changing ratio of tall vehicles, message rate 0.05*

As is shown in figure 5.11 and 5.12, the delay at a higher ratio of tall vehicles is smaller than the one at a lower ratio. During message propagation, a signal broadcast by tall vehicles reaches farther than the one from the low vehicles, since the obstacles in between the Tx and Rx affect

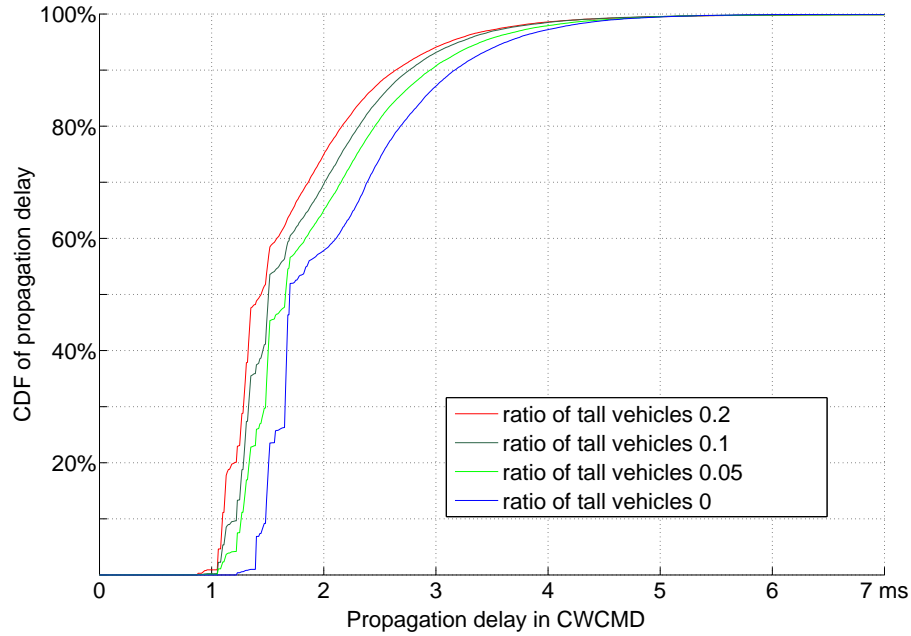


Figure 5.12: *The performance comparison of the CWCMD at changing ratio of tall vehicles, message rate 0.05*

the signal from tall Tx less than the signal from low vehicles. In other words, the tall vehicles help to improve the performance of delay by minimising the effect of obstacles and increasing the propagation distance. More tall vehicles leads to higher possibility that the Tx/Rx is a tall vehicle and therefore has a longer propagation distance. Note that with a higher ratio of tall vehicles, it is more likely that the obstacle(s) is/are the tall vehicle(s) which affect the signal propagation. Yet, the obstacle effect by tall vehicles is less dominant than the performance improvement. The effect of changing ratio of tall vehicles in both DBA-MAC and the CWCMD is similar.

5.5 Incorporating Vehicle Height in the BM Selection

The results in the previous section show that the height of the vehicle affects the signal propagation. Specifically, tall vehicles as obstacles block the signal and reduce the range of transmission. On the other hand, tall vehicles as Tx or Rx improve the network connectivity and thus suitable to be the intermediate nodes for a stable connection [34]. In this section, the height of the vehicles is included in the SI of the BM selection of the CWCMD to determine whether this

can improve the performance in a practical case for faster propagation.

During the BM selection, the heights of the vehicles are used to estimate the suitability of the candidates, as well as the relative distance. The tall vehicles are distributed on the road randomly and considering the height solely as the criterion of the candidates' suitability may result in an increase in the number of the hops and consequential longer delays. While considering the relative distance only as a suitability criterion, low vehicles may be the winners of the BM selection, which reduces the transmission range if the signal is blocked by tall vehicles. The purpose of considering height in assessing suitability is to balance the relative distance between the BMs and the transmission range. The proposal which combines the CWC, the MDC and also the vehicles' height is named as the CMH (CWC, MDC, Height).

In the CMH, SI is the product of the Distance Index (DI) and the Height Index (HI),

$$CW_i = (1 - SI_i)(CW_{max} - CW_{min}) + CW_{min} \quad (5.13)$$

$$SI_i = HI_i DI_i \quad (5.14)$$

$$DI_i = \frac{\min(\Delta s_i, \Delta s_i + \Delta v_i t)}{RR} \quad (5.15)$$

The value of HI is between 0 and 1 and is determined by the type of the vehicles, i.e. a tall vehicle or a low one. The HI for a tall vehicle is set as 1, and the one for a low vehicle is less than 1. The improved SI shows that for two vehicles with the same distance to the BM, the taller vehicle has a shorter backoff time than the low one. And for two vehicles with the same height, the vehicle farther from the BM has a shorter backoff. In the simulation of this thesis, the value of HI for low vehicles is set as 0.1, 0.5 and 0.9 to show the results of low vehicles at different priorities. The optimal configuration of HI and the relation between HI and system performance are left for future work.

5.5.1 Comparison between the CWH and the ESC

The simulation results of the CWH and a comparison between the CWH and a clustering protocol the ESC are presented in this part. The configuration of the system in the CWH is the same as the one in Section 5.4. The ratio of tall vehicles ranges from 0 to 0.2. The message rate in the simulation is set to 0.05.

The ESC [35, 36] is a clustering protocol which incorporates the vehicles' height in a clus-

terhead selection. Vehicles estimate their suitability as a clusterhead according to the relative speed and the relative distance to other vehicles as well as their height. When considering their suitability to be a clusterhead, vehicles with a lower relative speed are preferred over those with a high relative speed. A smaller distance is preferred, and tall vehicles are favoured over short vehicles. The suitability of a vehicle to be a clusterhead is quantified in the form of Coulomb's Law. Each individual vehicle calculates the relative force to all the neighbouring vehicles and the vehicles with the greatest total force are selected as the clusterheads.

$$F_{ij} = k_{ij} \frac{q_i q_j}{r_{ij}} \quad (5.16)$$

Equation 5.16 provides the relative force between vehicles i and j . Coefficient k_{ij} is determined by their relative movement and relative speed. If vehicles i and j are approaching each other, which means that the faster vehicle is following the slower vehicle, k_{ij} is defined as the reciprocal of their speed gap, $k_{ij} = \frac{1}{abs(\Delta v_{ij})}$. Otherwise, k_{ij} is the inverse of the speed gap, $k_{ij} = -abs(\Delta v_{ij})$. q_i and q_j are determined by k_{ij} . If $k_{ij} > 0$, $q_i, q_j = 2$; otherwise, $q_i, q_j = 0.5$. For tall vehicles, e.g. vehicle i , $q_i = 2$ regardless of the sign of k_{ij} . r_{ij} represents the relative distance between vehicles i and j .

Vehicles broadcast their speed and location by means of a periodic beacon. All of the vehicles calculate F_{ij} for each neighbour. $F_i = \sum_j F_{ij}$ shows the suitability of vehicles as a CH. The vehicle with the greatest F_i among the neighbours is selected as a clusterhead.

To make a direct comparison between the two selection schemes, the transmission scheme of the CWH is used as a basis for both selection schemes. Using this common transmission scheme, the performance of the two selection schemes will be evaluated through message delay. The CHs in the ESC are the counterparts of the BMs in the CWH.

Figure 5.13 shows that the messages are propagated with a longer delay in the ESC than in the CWH. This is due to the mechanism of CH/BM selection in the two schemes. In the CWH, the aim is to forward messages as fast as possible; therefore, the farthest candidates within the radio range have the highest suitability to be a BM. In the ESC, the association of a vehicle with all its neighbours is considered to determine its suitability, as is shown in Equation 5.16, since the stability of the CH links is the prime target in the ESC. The ESC selection scheme results in the CHs being distributed evenly throughout the radio range. From the standpoint of link stability, the link between a CH and the farthest vehicle is less stable than a link between a

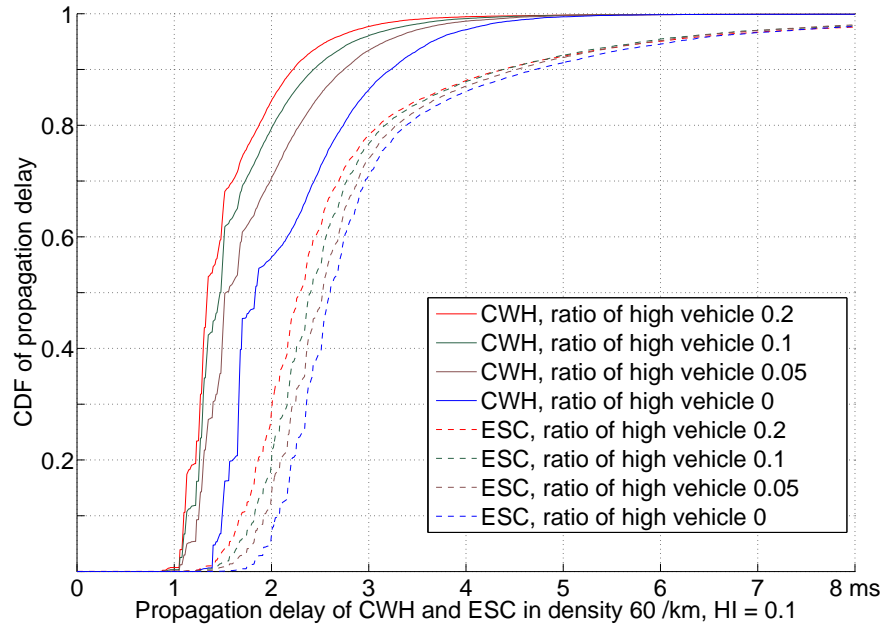


Figure 5.13: Performance comparison between ESC and CWH at a density of 60 per km and message rate 0.05

CH and a close vehicle, due to the dynamic nature of VANETs. Therefore, the farthest vehicle is not a suitable candidate to guarantee CH link stability. The criterion in the ESC lowers the distance between adjacent CHs and the number of hops and transmission times are greater than the CWH, which accounts for the performance gap shown in the figure. In both the CWH and the ESC, the height of the vehicles is used to measure the suitability of vehicles as intermediate nodes.

5.5.2 Impact of Height Index (HI) on the Performance of the CWH

This section presents the impact of HI on the performance of the CWH. The configuration of the system is the same as the one in Section 5.4. The ratio of tall vehicles is 0.1. The performance is compared to the one of the CWCMD, in which vehicle height is neglected, in various densities. In the second part of the section, the impact of the ratio of tall vehicles on performance is also presented.

The results in Figure 5.14 and Table 5.13 show that the CMH results in only a slight improvement in the system performance in terms of propagation delay as well as the average hop of

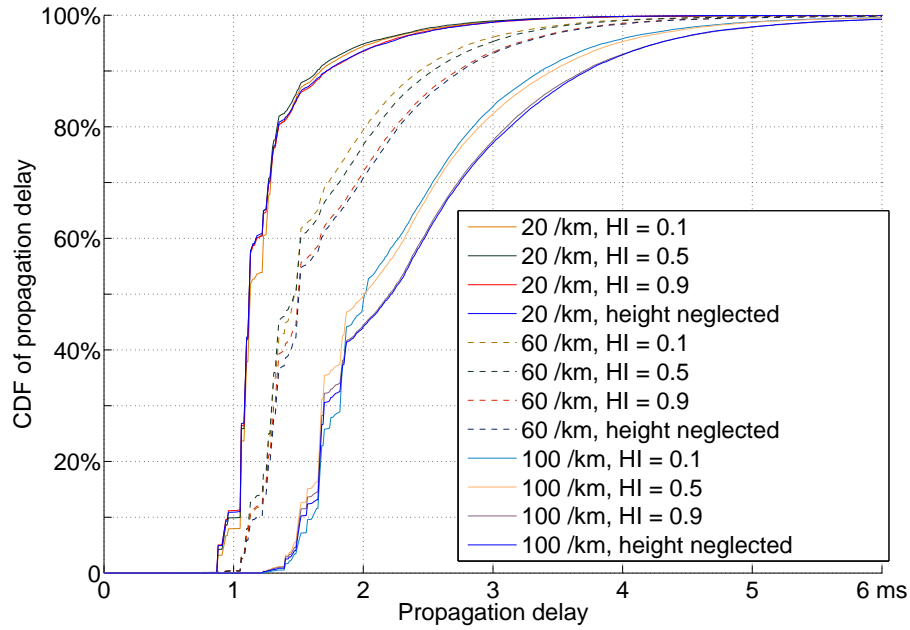


Figure 5.14: The performance comparison of the CWCMD with changing height at message rate 0.05

	HI = 0.1	HI = 0.5	HI = 0.9	neglecting height
Aver. BMs /km	5.70 ± 0.24	5.48 ± 0.20	5.53 ± 0.23	5.62 ± 0.23
High% in BMs	57.57%	48.40%	31.27%	26.97%
Aver. hop	7.76 ± 0.30	7.70 ± 0.29	7.89 ± 0.32	8.00 ± 0.34
Delay /ms	1.677 ± 0.149	1.694 ± 0.136	1.789 ± 0.161	1.811 ± 0.160

Table 5.13: Performance with consideration of height at a density of 60 per km

each message.

In the BM selection, the low vehicles which share the same CW with the tall vehicles are farther from the BM than the tall vehicles, due to the introduction of the HI. Assume the relative distance from the low vehicle to the BM is Δs_l , then the distance gap between low vehicles and tall vehicles with the same CW, i.e. D_g , is determined by the HI, $D_g = HI \Delta s_l$. If the relative distance of a low vehicle to the BM is not greater than the one of the tall vehicle by D_g , the tall vehicle will respond to the BM prior to the low one. The advantage in height makes the tall vehicles better intermediate nodes in terms of the transmission range. This accounts for the slight improvement of the propagation delay.

With the decrease of HI, the number of BMs in the unit distance and the ratio of tall vehicles rise. A smaller HI leads to the case where the tall vehicles win the contention with a higher probability than the low vehicles, although the tall vehicles may be closer to the BM than their low counterparts. The signals from the tall BMs, however, are less likely to be blocked than the low BMs and will propagate over a longer distance, which accounts for the smaller average number of BMs in the unit distance and the smaller average hop number, as $HI = 0.9$ and 0.5 . As HI reduces further, the relative distance becomes an increasingly weak factor in the selection criterion and the average number of BMs becomes greater than the one without any consideration of the vehicles' height, which also affects the hop number.

Note that the introduction of the HI increases the backoff time of the low vehicles. The improvement of performance, i.e. delay, comes at the cost that the formation time is increased. The comparison of the DEFT in varying density and the HI is presented in Figure 5.15.

The figure shows that with decrease of the HI, i.e. raising the priority of tall vehicles, the DEFT rises. The case of $HI = 1$ is that low vehicles share the same priority with tall ones, i.e. height is not considered. With the decrease of the HI, the reduction of the SI of a low vehicle is greater, compared to the case of $HI = 1$. The equivalent effect of the smaller HI for low vehicles is to reduce the relative distance to the BM. A tall vehicle which is not the best one in terms of its relative distance to the BM has a chance to win the contention. The backoff time of the winner therefore rises, which increases the network formation time. It is noticed that the performance change, i.e., a delay, caused by the consideration of height is negligible when compared with the DEFT. The major effect of considering height is the increase of network formation time. In terms of the DEFT, the CMH is not the optimal one, since the benefit of fast propagation is at

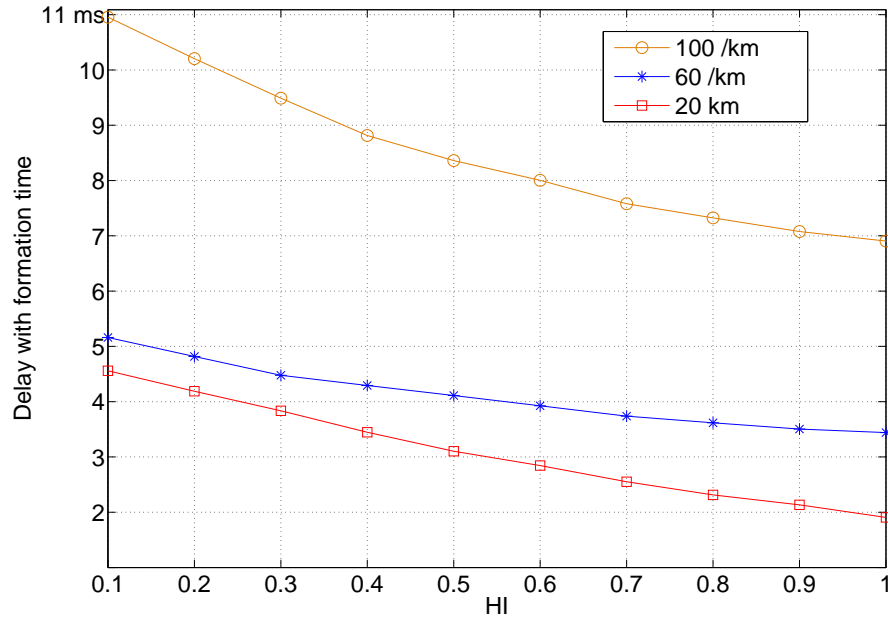


Figure 5.15: The comparison of the DEFT in the CWCMD with the height in varying densities at message rate 0.05

the cost of a longer backoff time of low vehicles in the procedure of the BM selection.

5.5.3 Impact of the Ratio of Tall Vehicles on the Performance of the CWH

In the above section, the ratio of tall vehicles is set to 0.1. In this part, the performance of the CMH at various ratios of tall vehicles will be presented to show how the tall vehicles affect the system performance. The ratio of tall vehicles in this section is set to 0, 0.05, 0.1 and 0.2.

Figure 5.16 shows the propagation delay of the CMH in various densities and ratios of tall vehicles. It is shown that at any density the performance in a greater ratio of tall vehicles is better than the performance in a low ratio of tall vehicles. In the CMH, the priority of tall vehicles is guaranteed by weakening the suitability of low vehicles. A greater ratio of tall vehicles leads to the condition of there being more tall vehicles in the BMs. The tall vehicles propagate the signal farther than the low vehicles, since the impact of obstacles on propagation is weaker when the Tx and/or Rx are tall vehicles; therefore, the rise in the ratio of tall vehicles in BMs increases the average distance between adjacent BMs. This accounts for the performance improvement as the ratio of tall vehicles rises.

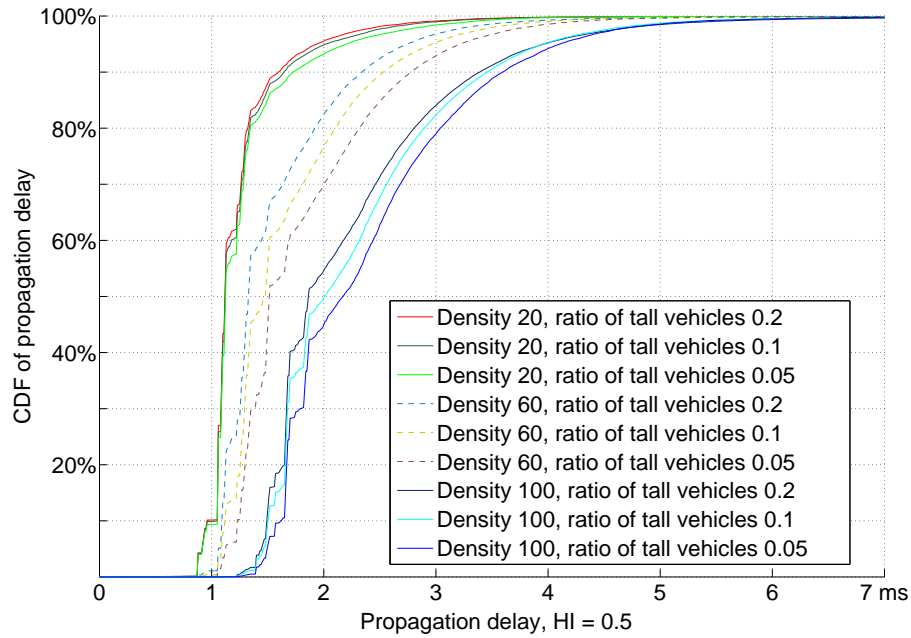


Figure 5.16: Performance of the CWCMD with consideration of the height at various ratios of tall vehicles and densities, $HI = 0.5$

Also, from the figure 5.16, the degree of performance improvement in high densities is more conspicuous than in low densities, i.e., 20 veh per km. At a low density, i.e. 20 veh per km, due to the sparse distribution of the vehicles, the effect of the obstacles between Tx and Rx is less than the effect in high densities and thus the benefit of using tall vehicles is limited. But, in high densities, the signal attenuation caused by obstacles between Tx and Rx is large and the use of tall vehicles significantly increases the propagation distance, as the Fresnel zone is higher and the propagation suffers less from vehicles in between the Tx and Rx.

5.6 Conclusion

The research in this chapter indicates that the vehicles in between the Tx and Rx affect signal propagation significantly. In fact, the performance in terms of propagation delay, as a function of the vehicle density, is the opposite of the case when obstacles are ignored. That is, performance of delay in dense traffic is better than in sparse traffic in ideal case. But performance in sparse traffic is better if incorporating obstacles in performance estimation. Ignoring the obstacle effect in estimating the system performance leads to significant errors. Therefore, obstacles

is recommended to be modelled when testing the design of protocols in VANETs to improve the accuracy of performance estimation.

Since tall vehicles provide better transmission range than low vehicles, an improved protocol the CMH that takes into account a vehicle's height is proposed. The results indicate that the consideration of height can improve the performance of delay, but at the cost of network formation time.

Chapter 6

Conclusion and Future Work

6.1 Summary of the Thesis and Conclusion

In this thesis, protocols aimed at fast propagation of safety messages in VANETs are proposed based on DBA-MAC and the impact of vehicles between the transmitter and receiver as obstacles on system performance are evaluated.

In Chapter 3, DBA-MAC is introduced, which is a cross-layer protocol for fast propagation of safety messages. Predefined BM are selected periodically and take charge of message forwarding. Analysis shows that the selection criterion of BMs in DBA-MAC and random selection in the CW scheme are barriers to improving performance in terms of fast propagation. Based on the analysis, a novel selection criterion (MDC) to determine the suitability of candidates is proposed, in which the minimum distance of the candidate to the previous BM throughout the period is adopted instead of the distance at the end of the period. The change of selection criterion aims to keep the distance between adjacent BMs as long as possible. Yet, the MDC solely changes the suitability of the leaving candidates. The difference caused by the MDC relates to the standard deviation of speed distribution. An extreme case is that if all the vehicles share a same speed, the MDC has little impact on the BM selection. In addition, the order of candidates' suitability is mainly determined by the location of vehicles at the beginning of each period. The MDC changes the suitability of leaving candidates but changes little about the rank of candidates' suitability which decides the BM selection more significantly.

The randomness of selection in the CW mechanism leads to the condition where candidates with weak suitability are able to become BMs, although with low probability. This weakens the performance of BMs distance and message propagation. The CWC is proposed to increase the probability that the candidates with the best suitability win in the contention. Simulations show that the proposed scheme improves the performance of message propagation in various densities of vehicles, ratios of safety messages and non-safety messages. The CWC can be applied to other VANET protocols in which a CW mechanism is adopted to communicate the

suitability of vehicles. The CWC improves the performance in terms of delay because the randomness of CW selection is limited. The smallest CW of candidates with weak suitability is always greater than the ones with better suitability. The randomness in the DCF scheme is to avoid collision among stations, yet it is not a good scheme to distinguish stations with different priorities. By limiting CW selection range, the CW lower boundary reflects the suitability of candidates directly and therefore the candidate distinction can be implemented.

In Chapter 4, the mathematical models for both the CWCMD and DBA-MAC are established to predict and validate the system performance. Numerical results of mathematical models show that 1) the distance between adjacent BMs in the CWCMD is longer than the one in DBA-MAC and close to the theoretical maximum as defined by order statistics, and 2) the CWC is the key factor to improve the system performance. Besides, network formation is evaluated by overhead/formation time in proactive protocols of VANETs. With the proposed metric DEFT, the configuration for optimal system performance can be found by adjusting CW-related parameters due to the restricting relation between the network formation time and propagation delay in the CW mechanism. The analysis and results indicate that fast propagation could be at the cost of long formation time and vice versa in the CWCMD. That is, improving performance of one metric solely, i.e., delay, leads to the degradation in the performance of the other metric, i.e., formation time, and vice versa. The direct effect of longer formation time, which reduces the average delay, is postponing the transmission of message propagation. Shorter formation time means longer delay. Therefore, the balance between shorter delay and shorter formation time should be kept in mind when adjusting the system parameters of the CWCMD.

In addition, analysis and simulation in this research show that the security distance between adjacent BMs affects the location distribution of vehicles, which is neglected in the assumption of Poisson distribution in the majority of existing research. In Chapter 4, a novel location distribution is proposed which considers this factor and provides a more realistic estimation of traffic. The ideal exponential distribution leads to increasing error with the rise of indices due to the lack of consideration of the practical factor, i.e., the security distance. If the security distance is incorporated, the error of theoretical distribution becomes much smaller and the theoretical distribution can be used to model the location distribution in simulations. The security distance is the key factor to enhance the availability of theoretical distribution.

In Chapter 5, a more practical scenario is considered, in which the vehicles in between the

transmitting vehicle and the receiver affect the signal reception by blocking the LOS. Analysis and simulations indicate that 1) the assumption that the vehicles in the maximum transmission range of the transmitting vehicle are able to receive the signal equally is not suitable in the practical scenario, 2) whether the signal can be received is related to the number of obstacles and the distance between Tx and potential Rx, 3) the impact of vehicles as obstacles is significant to the system performance, and 4) system performance, e.g. propagation delay, at a higher density, when considering the effect of obstacles, is worse than at a lower density which is the opposite to the ideal case without consideration of obstacles. The existence of obstacles changes the network connectivity and possible transmission range, which results in dramatic change of system performance. Even the trend of performance is reversed by the obstacles. Therefore, the obstacle effect caused by vehicles is an important factor to be considered when evaluating protocol performance as well as designing VANETs protocols. It is often assumed that vehicles between the transmitter and the receiver take no impact on signal propagation in existing literatures. This research indicates that the obstacle effect should be incorporated in protocol design and performance estimation to improve the accuracy and to make the research on VANETs available and valuable.

6.2 Future Work

6.2.1 Interference of Vehicles and Roadside Buildings in Signal Propagation

In this thesis, the impact of vehicles between the transmitting vehicle and receiver as obstacles on signal propagation and network connectivity are analysed. Only the signal from the LOS part is considered, since it dominates the signal received, especially in the highway scenario. Other factors, e.g. reflection/scattering from vehicles on the road surface and roadside building, are neglected. How the signal is affected by the reflection/scattering caused by vehicles and roadside buildings, especially in an urban scenario is an interesting topic for future work, which is very useful for the analysis of the system performance of VANETs in practice. The analysis of interference in signal propagation will offer a tool for performance estimation of VANET protocols in practical scenarios.

6.2.2 Low Penetration Ratio of VANET Devices

The work in this thesis assumes that every vehicle in a VANET is equipped with a wireless device and can be involved in information exchange or forwarding. Yet, at the initial stage of commercialisation, the penetration ratio of VANET devices could be low, which makes the possible VANET a sparse network. The network connectivity and efficiency of information propagation directly affect the benefit and development of VANETs. How to implement efficient propagation in low penetration ratios is an interesting technical topic to attract more users in the initial stage of VANETs. Adaptation of the store-carry-forward scheme which is designed for disconnected networks can be one solution for the case of low penetration ratios. The other possible solution is to increase the transmission power for higher connectivity. The relation between a threshold of connectivity and transmission range for low penetration ratio, e.g. 10%, 20%, is an interesting topic to be studied.

6.2.3 Urban Scenario: Performance Estimation of the Proposed Protocol and Protocol Design

The environment of the work in this thesis is the highway scenario, in which the traffic is more simple than the urban scenario. The urban environment brings more complexity to the research, e.g. variable speed, changing vehicle density and turning or stopping at road corners. The work in this thesis proves that the speed and the density make an impact on network communications. In addition, the leaving and merging of vehicles in the network affects the density and speed and, further, the communication, the case being worse if the leaving vehicles are the BMs. To estimate the performance of the protocol in an urban scenario as well as design protocols dedicated to urban traffic, a traffic model of the urban case should be designed/used, which includes the features of urban traffic, e.g. merging and leaving of vehicles, vehicles gathering near traffic lights, a broader range of speed, and so on.

Appendix A

Extended results of Chapter 3

A.1 Impact of the Message Rate on Performance at Various Densities in both DBA-MAC and the Proposals

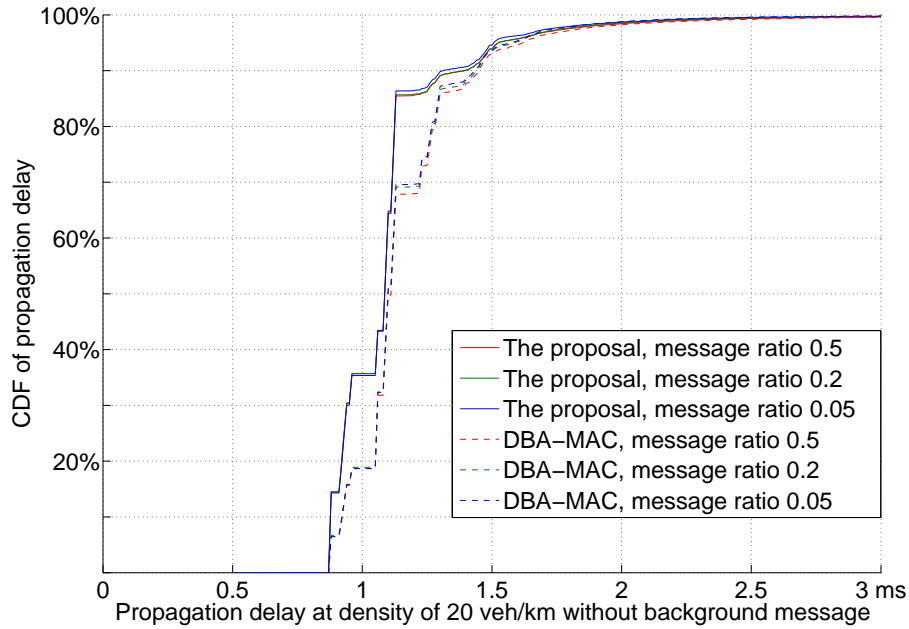


Figure A.1: *The CDF of propagation delay in both DBA-MAC and the CWCMD at a density of 20 veh/km with the changing ratio of the message rate*

Figure A.1 shows that the various message rates affect the performance of DBA-MAC and the proposals insignificantly at a density of 20, since at a low density the absolute number of safety messages is small enough to be unable to affect the propagation of other messages. While at a density of 100 (figure A.2), the effect of the message rate on the performance is greater than at a low density. This is because at a high density the absolute number of messages is greater, provided that the message rate is the same. More messages increase the possibility of collision

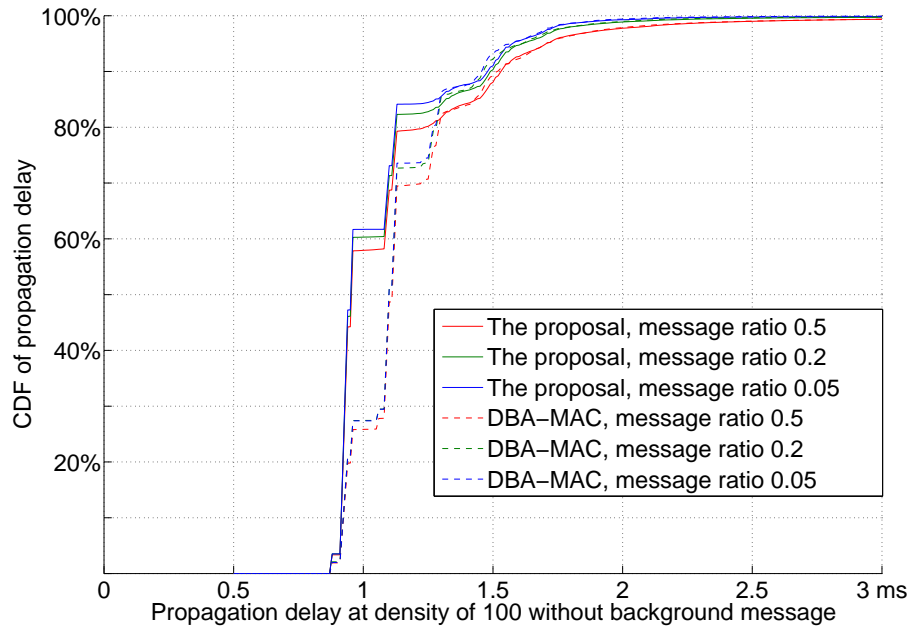


Figure A.2: *The CDF of propagation delay in both DBA-MAC and the CWCMD at a density of 100 veh/km with the changing ratio of the message rate*

and the average waiting time of vehicles to transmit messages, which accounts for the more conspicuous gap of performance caused by the higher message rate.

Appendix B

Extended results of Chapter 4

B.1 Theoretical Comparison between DBA-MAC and the Proposals at a Variety of Densities

Besides the results of the density shown in the content, i.e., 60 veh/km, a theoretical comparison at a density of 100 and 20 veh/km is presented here.

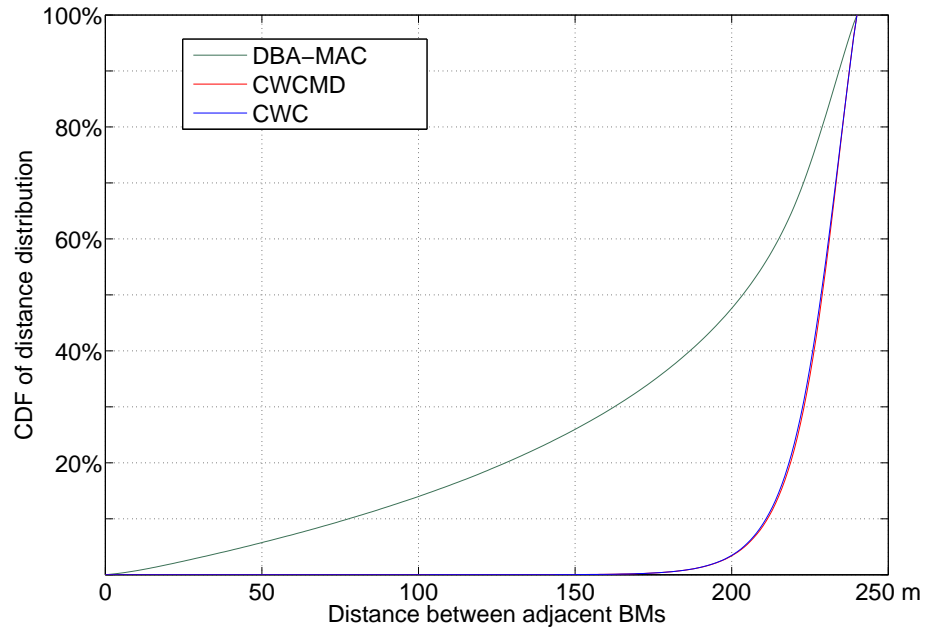


Figure B.1: *The CDF of distance distribution between adjacent BM in both DBA-MAC and the proposals at a density of 100 veh/km*

Figure B.1 and figure B.2 show similar features with the results at a density of 60 veh/km, i.e. 1) the relative distance of BMs in DBA-MAC spreads from 0 to the radio range 240 m; 2) the BMs in proposals locate closer to the edge of the radio range.

In DBA-MAC, every candidate within the radio range is able to win the contention, although

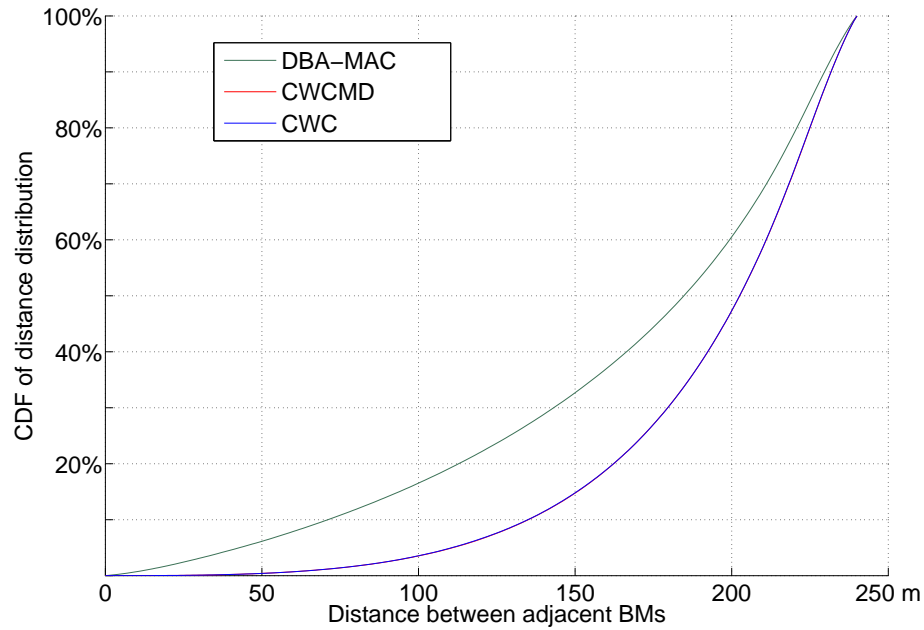


Figure B.2: *The CDF of distance distribution between adjacent BM in both DBA-MAC and the proposals at a density of 20 veh/km*

with various winning probabilities, which accounts for the spread of distance distributions. In the proposals, those candidates with greater suitability finish their waiting time before transmission prior to the other candidates, which is the reason for the BMs closer to the edge of the radio range. The advantage of the proposals over DBA-MAC is that they are free from the impact of vehicle density.

It can also be noticed that in DBA-MAC the performance of distance distribution is better at a density of 100 than of 20. At a higher density, due to the uniform distribution of vehicles' location on the road, there are more vehicles in the area close to the edge of the radio range on average, e.g. 200 - 240 metres. Inversely, it is highly possible that there are less vehicles or even no vehicles in the same area at a lower density, e.g. 20 veh/km. Considering the greater suitability of the vehicles in the area close to the edge of the radio range, they will win the contention with a higher probability than other vehicles and accordingly a higher ratio of vehicles become the next BMs at the higher density.

The results also indicate that the BMs in the proposals at the higher density are closer to the edge of the radio range than those at the lower density. According to the theory of order statis-

tics [60], once there are more candidates in the contention, the location of the candidate with the highest suitability (the last candidate on the assumption that there is no speed) is closer to the edge of the radio range, which accounts for the greater distance between adjacent BMs on average.

B.2 Theoretical Comparison between the Results of Order Statistics and Proposals at a Variety of Densities

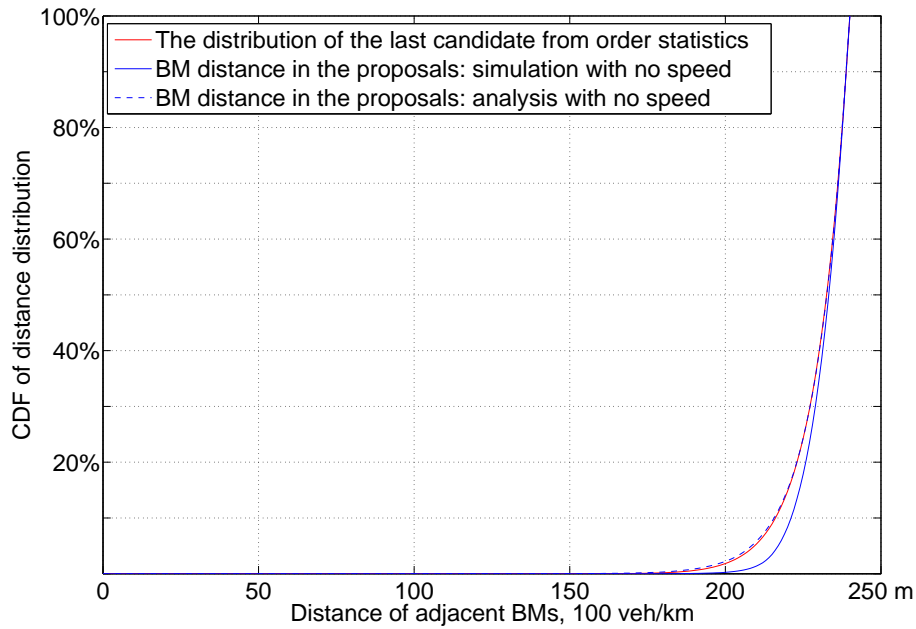


Figure B.3: *The CDF comparison between the simulation of the proposals with no speed distribution and the last candidate in order statistics, density 100*

Figures B.3 and figure B.4 present the theoretical results of the location distribution of the last candidate at a density of 100 and 20 from the theory of order statistics. Since the theoretical location of the last candidate at a high density is closer to the edge of the radio range, the relative distance of BMs at a high density is greater than the relative distance at a low density, which accounts for the performance gap of the proposals at different densities.

In the results of the proposal, the index of the last candidate is not a constant value considering the radio range and the vehicles' density. For example, the index of the last candidate can be 4,

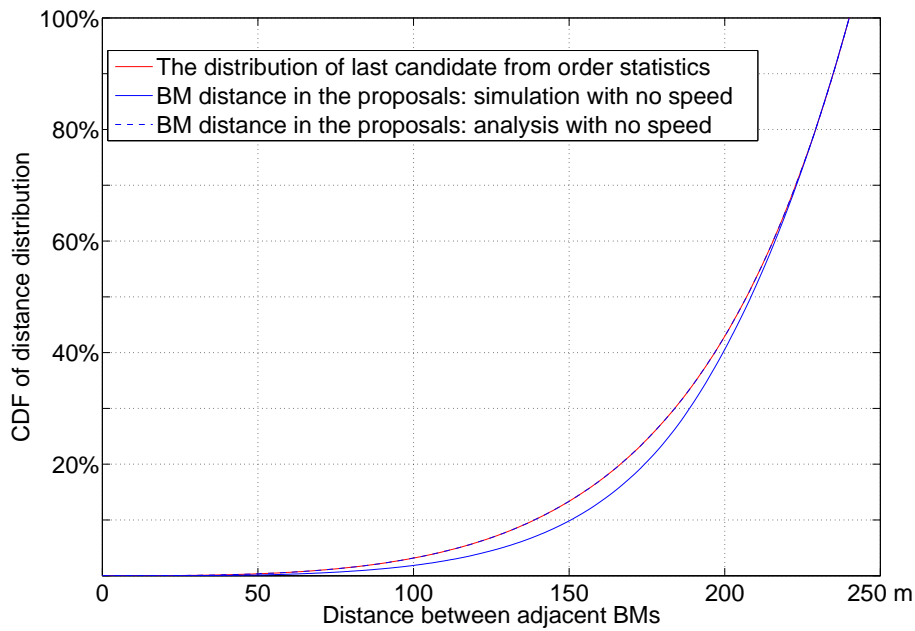


Figure B.4: *The CDF comparison between the simulation of the proposals with no speed distribution and the last candidate in order statistics, density 20*

5 or 6 in different cases of a density of 20 veh/km. Therefore, the curve of the proposal is the weighted result of the indices in a variety of cases, i.e., about 4.8 at a density of 20. While the results of order statistics must be from an integer, i.e., 5 at a density of 20 and 24 at a density of 100, the difference between the indices of the proposals and order statistics leads to the gap in the CDF curves between the theoretical results of order statistics and the results with no speed. Note that at a density of 100 and 60, the weighted indices from the analysis are close to the indices of the vehicles from order statistics, the gap between the theoretical results and the analysis results is almost zero.

Appendix C

Extended results of Chapter 5

C.1 The Connection Probability at Various Densities and the Ratio of Tall Vehicles

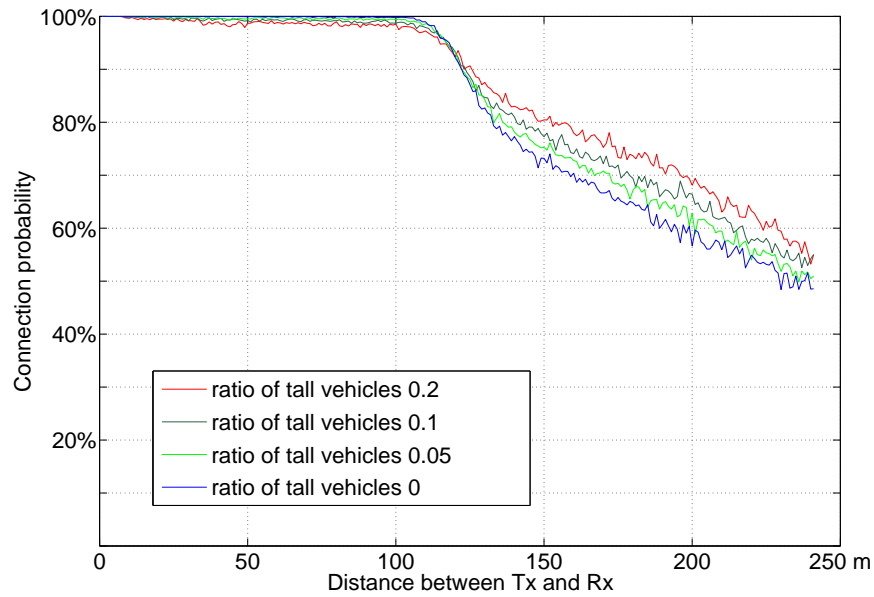


Figure C.1: Connection Probability of vehicles at a density of 20 /km at various ratios of tall vehicles

Figure C.1, C.2, and C.3 present the connection probability at various densities and various ratios of tall vehicles.

At a low density, the number of obstacles in between Tx and Rx is smaller than the one at a high density, which accounts for the lower connection probability at a high density at the same location.

The probability of there being no obstacle between Tx and Rx decreases with the rise of the distance which is due to the distribution of the vehicles. Therefore, the attenuation caused by

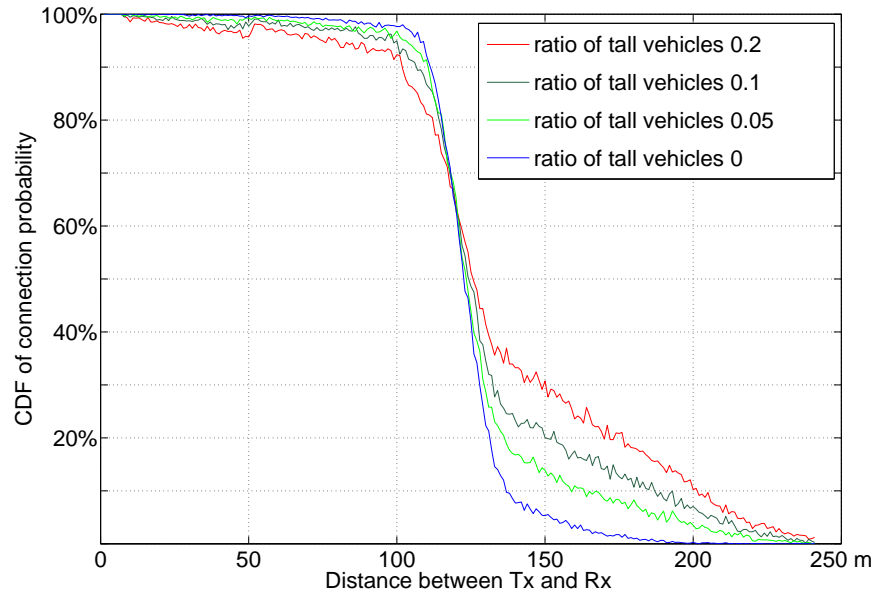


Figure C.2: Connection Probability of vehicles at a density of 60 /km at various ratios of tall vehicles

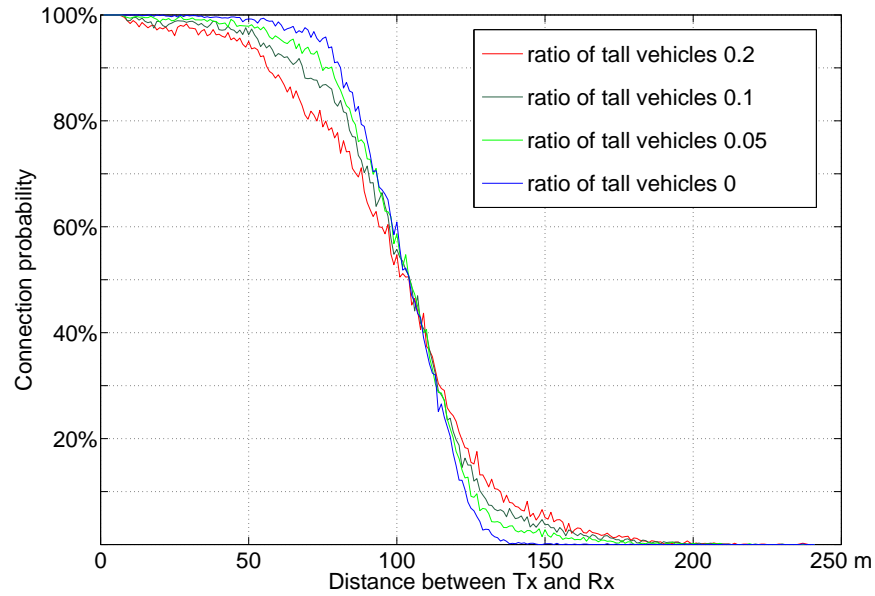


Figure C.3: Connection Probability of vehicles at a density of 100 /km at various ratios of tall vehicles

obstacle(s) is increasingly greater with the rise of the distance. In addition, the path loss is an exponential function of the distance which is also the factor of reducing signal strength at the receivers.

In addition, the figures show that at the same density the connection probability is higher for the case of the high ratio of tall vehicles near distance 0, but is overtaken by the low ratio of tall vehicles as the distance approaches the edge of the radio range. The radio range is divided into three parts, 1) close distance, 2) middle distance, and 3) far distance.

1) At a close distance, i.e., less than 100 m, since the signal strength loss by distance is relatively small, the main factor which affects the signal strength at Rx is the case where obstacle(s) in between Tx and Rx is/are taller than Tx and Rx, i.e., tall obstacle(s) and short Tx and Rx. The occurrence of this type of case depends on the ratio of tall vehicles. As the ratio is 0.2, the probability is 12.8%(80%*20%*80%). In general, it is $a^2(1 - a)$ where a is the ratio of tall vehicles. In the case of a lower ratio than 0.2, the occurrence of such cases get less frequent and therefore the connection probability is higher in the lower ratio of tall vehicles.

2) In the middle distance, the common feature of connection probability at all densities is that a sharp slope occurs on the curves. The sharp drop of the curves is caused by the sharp increase of the probability of the obstacle(s) cases, which makes significant impact on the signal strength and connection.

Take the density of 60 veh/km as an example. The probability of one obstacle, two obstacles and more, as is shown in figure C.4, rises with the distance, sharply from 100 metres (twice that of the security distance 50m). In the range from 100m to 150m, the case of one obstacle becomes the predominant case, the probability of which is above 50%. The dramatic rise of the probability of one obstacle is the reason why the connection probability drops sharply in this range, since the signal attenuation caused by one obstacle in this range is great enough to disconnect the link between Tx and Rx. This is proved by the connection probability by individual cases of obstacle numbers in different ratios of tall vehicles, as is shown in figure C.5 and C.6. In both figures, the connection probability drops dramatically in the middle range, which is the joint effect of path loss and attenuation by obstacle(s), especially in the case of one obstacle.

3) At a distance close to the edge of the radio range, the cases of no obstacle effect play a predominant role in the network connection, because in this range the path loss is large enough

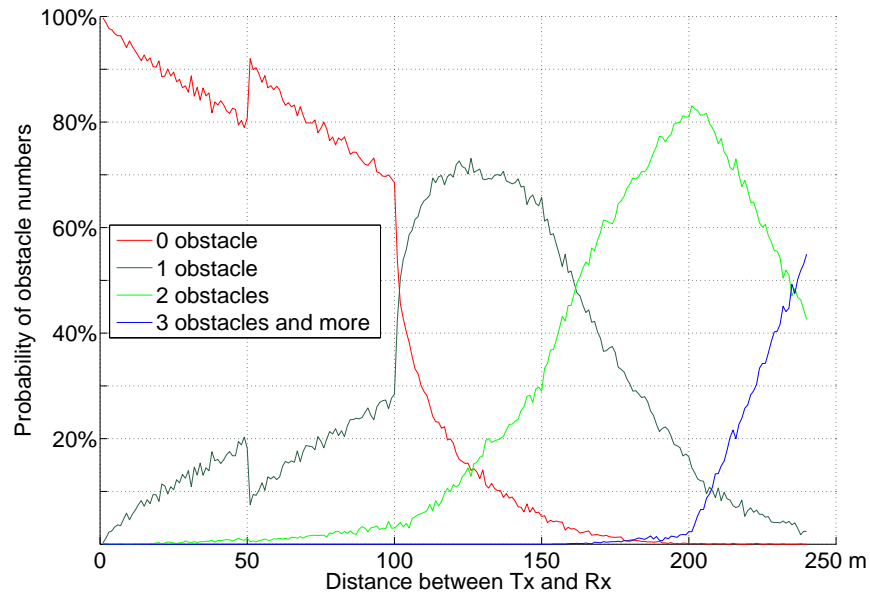


Figure C.4: *Probability of obstacle numbers*

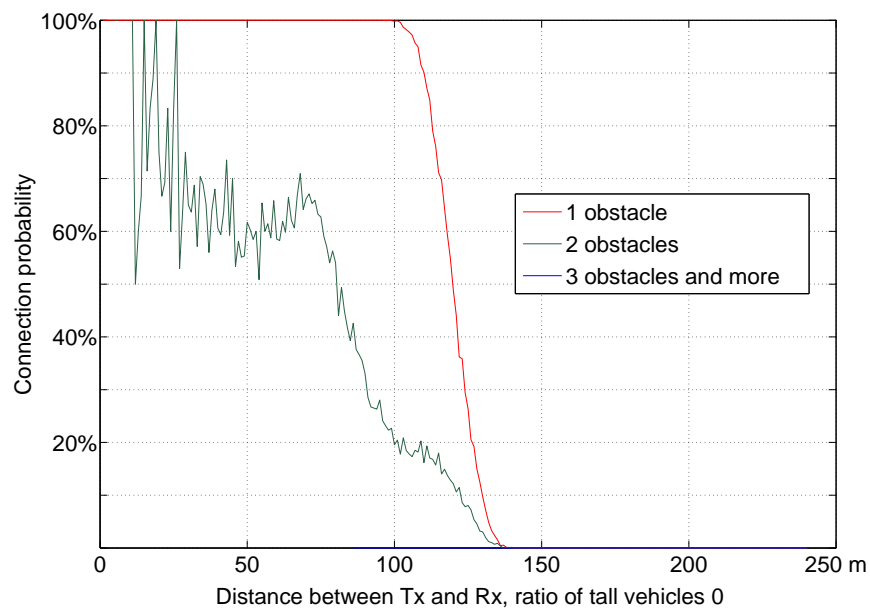


Figure C.5: *Connection probability by obstacles, ratio of tall vehicles 0*

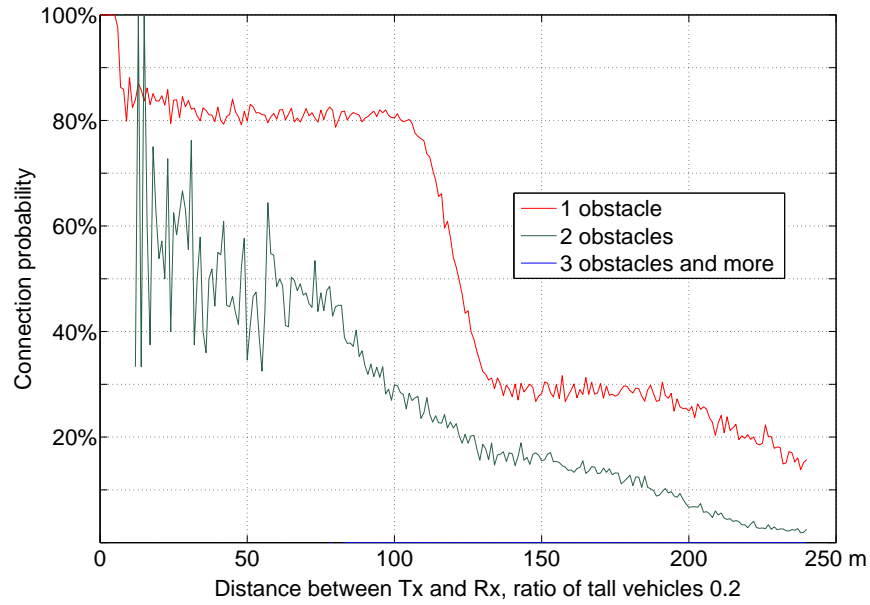


Figure C.6: Connection probability by obstacles, ratio of tall vehicles 0.2

that the signal strength received is likely to fall below the threshold of the receiver and the obstacles affect the link more easily than at the close distance and middle distance. Since the probability of there being no obstacle is almost zero as we get closer to the edge of the radio range, the cases where obstacles cause little attenuation matter, i.e., tall Tx/Rx and short obstacle(s), tall Tx (or Rx) and short Rx (or Tx) and obstacle(s). The total probability of these cases at the ratio of 20% tall vehicles is 28.8% which is greater than the probability of 17.1% at the ratio of 10% (figure 5.5) and 0 at the ratio of 0%(figure C.5). This accounts for the higher connection probability at a distance close to the edge of the radio range in a higher ratio of tall vehicles.

Bibliography

- [1] IEEE 802.11 Working Group. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. page 2793, 2012.
- [2] S. Panichpapiboon and W. Pattara-Atikom. Connectivity Requirements for Self-Organizing Traffic Information Systems. *Vehicular Technology, IEEE Transactions on*, 57(6):3333–3340, 2008.
- [3] G. Karagiannis, O. Altintas, E. Ekici, G. Heijenk, B. Jarupan, K. Lin, and T. Weil. Vehicular Networking: A Survey and Tutorial on Requirements, Architectures, Challenges, Standards and Solutions. *Communications Surveys Tutorials, IEEE*, 13(4):584–616, 2011.
- [4] Y. Toor, P. Muhlethaler, and A. Laouiti. Vehicle Ad Hoc networks: Applications and Related Technical issues. *Communications Surveys Tutorials, IEEE*, 10(3):74–88, 2008.
- [5] D. Jiang and L. Delgrossi. IEEE 802.11p: Towards an International Standard for Wireless Access in Vehicular Environments. In *Vehicular Technology Conference, 2008. VTC Spring 2008. IEEE*, pages 2036–2040, 2008.
- [6] IEEE Std 802.11p IEEE 802.11 Working Group. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Amendment 6: Wireless Access in Vehicular Environments,. *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, 2010.
- [7] Xiang Weidong, Gozalvez Javier, Niu Zhisheng, Altintas Onur, and Ekici Eylem. Wireless Access in Vehicular Environments. *EURASIP Journal on Wireless Communications and Networking*, 2009, 2009.
- [8] Fan Li and Yu. Wang. Routing in Vehicular Ad Hoc Networks: A Survey. *Vehicular Technology Magazine, IEEE*, 2(2):12–22, 2007.
- [9] Kevin C Lee, Uichin Lee, and Mario Gerla. Survey of Routing Protocols in Vehicular Ad Hoc Networks. *Advances in Vehicular Ad-Hoc Networks: Developments and Challenges, IGI Global*, 21, 2009.

- [10] J.B. Kenney. Dedicated Short-Range Communications (DSRC) Standards in the United States. *Proceedings of the IEEE*, 99(7):1162–1182, 2011.
- [11] Giuseppe Bianchi, Luigi Fratta, and Matteo Oliveri. Performance Evaluation and Enhancement of the CSMA/CA MAC Protocol for 802.11 Wireless LANs. In *Personal, Indoor and Mobile Radio Communications, 1996. PIMRC'96., Seventh IEEE International Symposium on*, volume 2, pages 392–396. IEEE, 1996.
- [12] Giuseppe Bianchi and Ilenia Tinnirello. Remarks on IEEE 802.11 DCF Performance Analysis. *IEEE communications letters*, 9(8):765–767, 2005.
- [13] N. Wisitpongphan, O.K. Tonguz, J.S. Parikh, P. Mudalige, F. Bai, and V. Sadekar. Broadcast Storm Mitigation Techniques in Vehicular Ad Hoc Networks. *Wireless Communications, IEEE*, 14(6):84–94, 2007.
- [14] W. Viriyasitavat, O.K. Tonguz, and Fan Bai. UV-CAST: an Urban Vehicular Broadcast Protocol. *Communications Magazine, IEEE*, 49(11):116–124, 2011.
- [15] M. Zhang and R.S. Wolff. Routing Protocols for Vehicular Ad Hoc Networks in Rural Areas. *Communications Magazine, IEEE*, 46(11):126–131, 2008.
- [16] Luciano Bononi, Marco Di Felice, and Sara Pizzi. DBA-MAC: Dynamic Backbone-Assisted Medium Access Control Protocol for Efficient Broadcast in VANETs. *Journal of Interconnection Networks*, 10(04):321–344, 2009.
- [17] C. Shea, Behnam Hassanabadi, and S. Valaee. Mobility-Based Clustering in VANETs Using Affinity Propagation. In *Global Telecommunications Conference, 2009. GLOBE-COM 2009. IEEE*, pages 1–6, 2009.
- [18] A. Ahizoune and A. Hafid. A New Stability based Clustering Algorithm (SBCA) for VANETs. In *Local Computer Networks Workshops (LCN Workshops), 2012 IEEE 37th Conference on*, pages 843–847, 2012.
- [19] Sung-Ju Lee and M. Gerla. AODV-BR: Backup Routing in Ad Hoc Networks. In *Wireless Communications and Networking Conference, 2000. WCNC. 2000 IEEE*, volume 3, pages 1311–1316 vol.3, 2000.
- [20] O. Abedi, M. Fathy, and J. Taghiloo. Enhancing AODV Routing Protocol using Mobility Parameters in VANET. In *Computer Systems and Applications, 2008. AICCSA 2008. IEEE/ACS International Conference on*, pages 229–235, 2008.

- [21] Ben Ding, Zehua Chen, Yan Wang, and Hui Yu. An Improved AODV Routing Protocol for VANETs. In *Wireless Communications and Signal Processing (WCSP), 2011 International Conference on*, pages 1–5, 2011.
- [22] O. Abedi, R. Berangi, and M.A. Azgomi. Improving Route Stability and Overhead on AODV Routing Protocol and Make it Usable for VANET. In *Distributed Computing Systems Workshops, 2009. ICDCS Workshops '09. 29th IEEE International Conference on*, pages 464–467, 2009.
- [23] Brad Karp and Hsiang-Tsung Kung. GPSR: Greedy Perimeter Stateless Routing for Wireless Networks. In *Proceedings of the 6th annual international conference on Mobile computing and networking*, pages 243–254. ACM, 2000.
- [24] H. Menouar, M. Lenardi, and F. Filali. Movement Prediction-Based Routing (MOPR) Concept for Position-Based Routing in Vehicular Networks. In *Vehicular Technology Conference, 2007. VTC-2007 Fall. 2007 IEEE 66th*, pages 2101–2105, 2007.
- [25] Yan-Bo Wang, Tin-Yu Wu, Wei-Tsong Lee, and Chih-Heng Ke. A Novel Geographic Routing Strategy over VANETs. In *Advanced Information Networking and Applications Workshops (WAINA), 2010 IEEE 24th International Conference on*, pages 873–879, 2010.
- [26] E. Fasolo, A. Zanella, and M. Zorzi. An Effective Broadcast Scheme for Alert Message Propagation in Vehicular Ad hoc Networks. In *Communications, 2006. ICC '06. IEEE International Conference on*, volume 9, pages 3960–3965, 2006.
- [27] M. Al-Rabayah and R. Malaney. A New Scalable Hybrid Routing Protocol for VANETs. *Vehicular Technology, IEEE Transactions on*, 61(6):2625–2635, 2012.
- [28] H. Rahbar, K. Naik, and A. Nayak. DTSG: Dynamic Time-stable Geocast Routing in Vehicular Ad Hoc Networks. In *Ad Hoc Networking Workshop (Med-Hoc-Net), 2010 The 9th IFIP Annual Mediterranean*, pages 1–7, 2010.
- [29] Qiangyuan Yu and G. Heijenk. Abiding Geocast for Warning Message Dissemination in Vehicular Ad Hoc Networks. In *Communications Workshops, 2008. ICC Workshops '08. IEEE International Conference on*, pages 400–404, 2008.

- [30] C. Maihofer and R. Eberhardt. Geocast in Vehicular Environments: Caching and Transmission Range Control for Improved Efficiency. In *Intelligent Vehicles Symposium, 2004 IEEE*, pages 951–956, 2004.
- [31] A. Lakas and M. Shaqfa. Geocache: Sharing and Exchanging Road Traffic Information Using Peer-to-Peer Vehicular Communication. In *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*, pages 1–7, 2011.
- [32] G. Acosta and M.-A. Ingram. Model Development for the Wideband Expressway Vehicle-to-Vehicle 2.4 GHz Channel. In *Wireless Communications and Networking Conference, 2006. WCNC 2006. IEEE*, volume 3, pages 1283–1288, 2006.
- [33] A. Paier, J. Karedal, N. Czink, H. Hofstetter, C. Dumard, T. Zemen, F. Tufvesson, A.F. Molisch, and C.F. Mecklenbrauker. Car-to-car Radio Channel Measurements at 5 GHz: Pathloss, Power-delay Profile, and Delay-Doppler Spectrum. In *Wireless Communication Systems, 2007. ISWCS 2007. 4th International Symposium on*, pages 224–228, 2007.
- [34] M. Boban, R. Meireles, J. Barros, O. Tonguz, and P. Steenkiste. Exploiting the Height of Vehicles in Vehicular Communication. In *Vehicular Networking Conference (VNC), 2011 IEEE*, pages 163–170, 2011.
- [35] L.A Maglaras and D. Katsaros. Enhanced Spring Clustering in VANETs with Obstruction Considerations. In *Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th*, pages 1–6, June 2013.
- [36] L.A Maglaras and D. Katsaros. Distributed Clustering in Vehicular Networks. In *Wireless and Mobile Computing, Networking and Communications (WiMob), 2012 IEEE 8th International Conference on*, pages 593–599, Oct 2012.
- [37] G. Bianchi. Performance Analysis of the IEEE 802.11 Distributed Coordination Function. *Selected Areas in Communications, IEEE Journal on*, 18(3):535–547, March 2000.
- [38] Zuyuan Fang, Brahim Bensaou, and Yu Wang. Performance Evaluation of a Fair Backoff Algorithm for IEEE 802.11 DFWMAC. In *IEEE 802.11 DFWMAC, ACM MOBIHOC*, pages 48–57, 2002.
- [39] Reinhard Diestel. *Graph theory*. Heidelberg ; New York : Springer, 2010.

- [40] Seh Chun Ng, Wuxiong Zhang, Yu Zhang, Yang Yang, and Guoqiang Mao. Analysis of Access and Connectivity Probabilities in Vehicular Relay Networks. *Selected Areas in Communications, IEEE Journal on*, 29(1):140–150, 2011.
- [41] A Abdrabou and Weihua Zhuang. Probabilistic Delay Control and Road Side Unit Placement for Vehicular Ad Hoc Networks with Disrupted Connectivity. *Selected Areas in Communications, IEEE Journal on*, 29(1):129–139, January 2011.
- [42] S. Panichpapiboon and W. Pattara-Atikom. Exploiting Wireless Communication in Vehicle Density Estimation. *Vehicular Technology, IEEE Transactions on*, 60(6):2742–2751, July 2011.
- [43] Lin Cheng and S. Panichpapiboon. Effects of Intervehicle Spacing Distributions on Connectivity of VANET: A Case Study from Measured Highway Traffic. *Communications Magazine, IEEE*, 50(10):90–97, 2012.
- [44] N. Wisitpongphan, Fan Bai, P. Mudalige, V. Sadekar, and O. Tonguz. Routing in Sparse Vehicular Ad Hoc Wireless Networks. *Selected Areas in Communications, IEEE Journal on*, 25(8):1538–1556, 2007.
- [45] Xuexiang Jin, Yi Zhang, Fa Wang, Li Li, Danya Yao, Yuelong Su, and Zheng Wei. Departure Headways at Signalized Intersections: A Log-normal Distribution Model Approach. *Transportation Research Part C: Emerging Technologies*, 17(3):318–327, 2009.
- [46] Gongjun Yan and S. Olariu. A Probabilistic Analysis of Link Duration in Vehicular Ad Hoc Networks. *Intelligent Transportation Systems, IEEE Transactions on*, 12(4):1227–1236, Dec 2011.
- [47] S. Panichpapiboon and Lin Cheng. Irresponsible Forwarding Under Real Intervehicle Spacing Distributions. *Vehicular Technology, IEEE Transactions on*, 62(5):2264–2272, Jun 2013.
- [48] M. Ferreira, H. Conceicao, R. Fernandes, and O.K. Tonguz. Urban Connectivity Analysis of VANETs through Stereoscopic Aerial Photography. In *Vehicular Technology Conference Fall (VTC 2009-Fall), 2009 IEEE 70th*, pages 1–3, 2009.
- [49] M.M. Artimy, William J. Phillips, and W. Robertson. Connectivity with Static Transmission Range in Vehicular Ad Hoc Networks. In *Communication Networks and Services Research Conference, 2005. Proceedings of the 3rd Annual*, pages 237–242, 2005.

- [50] S. Yousefi, E. Altman, and R. El-Azouzi. Study of Connectivity in Vehicular Ad Hoc Networks. In *Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks and Workshops, 2007. WiOpt 2007. 5th International Symposium on*, pages 1–6, 2007.
- [51] A. Cardote, S. Sargento, and P. Steenkiste. On the Connection Availability between Relay Nodes in a VANET. In *GLOBECOM Workshops (GC Wkshps), 2010 IEEE*, pages 181–185, 2010.
- [52] Junghoon Lee and Cheol Min Kim. A Roadside Unit Placement Scheme for Vehicular Telematics Networks. In *Advances in Computer Science and Information Technology*, pages 196–202. Springer, 2010.
- [53] M. Boban, T. T V Vinhoza, M. Ferreira, J. Barros, and O.K. Tonguz. Impact of Vehicles as Obstacles in Vehicular Ad Hoc Networks. *Selected Areas in Communications, IEEE Journal on*, 29(1):15–28, 2011.
- [54] R. Meireles, M. Boban, P. Steenkiste, O. Tonguz, and J. Barros. Experimental Study on the Impact of Vehicular Obstructions in VANETs. In *Vehicular Networking Conference (VNC), 2010 IEEE*, pages 338–345, 2010.
- [55] S. Romaszko and C. Blondia. Bounds Selection - Dynamic Reset Protocol for Wireless Ad Hoc LANs. In *Wireless Communications and Networking Conference, 2007.WCNC 2007. IEEE*, pages 248–253, 2007.
- [56] Adlen Ksentini, Abdelhamid Nafaa, Abdelhak Gueroui, and Mohammed Naimi. Determinist Contention Window Algorithm for IEEE 802.11. In *Personal, Indoor and Mobile Radio Communications, 2005. PIMRC 2005. IEEE 16th International Symposium on*, volume 4, pages 2712–2716. IEEE, 2005.
- [57] Claudio E Palazzi, Marco Roccetti, Stefano Ferretti, Giovanni Pau, and Mario Gerla. Online Games on Wheels: Fast Game Event Delivery in Vehicular Ad-hoc Networks. *IEEE Intelligent Transportation Systems Society*, pages 42–49, 2007.
- [58] Claudio E Palazzi, Marco Roccetti, and Stefano Ferretti. An Intervehicular Communication Architecture for Safety and Entertainment. *Intelligent Transportation Systems, IEEE Transactions on*, 11(1):90–99, 2010.
- [59] John G Proakis and Masoud Salehi. *Fundamentals of communication systems*. Pearson Education India, 2007.

- [60] Barry C Arnold, Narayanaswamy Balakrishnan, and H Haikady Navada Nagaraja. *A first course in order statistics*, volume 54. Siam, 1992.
- [61] H. N. Nagaraja H. A. David. *Order Statistics*. John Wiley & Sons, Inc., 2003.
- [62] VS Bagad. *Wireless Communication*. Technical Publications, 2009.
- [63] ITU-R. Propagation by diffraction. In *International Telecommunication Union Radio-communication Sector, Geneva, Recommendation P.526*, Feb. 2012.
- [64] Rodney Vaughan. *Channels, propagation and antennas for mobile communications*, volume 50. Iet, 2003.
- [65] Luca Anchora, Luca Casone, Giovanni Ciccicarese, Mario De Blasi, Pierluigi Marra, and Cosimo Palazzo. An Optimal Setting for the Parameters of an Intelligent Flooding Scheme in VANETs. In *Wireless Conference (EW), 2010 European*, pages 332–338. IEEE, 2010.
- [66] Katrin Bilstrup, Elisabeth Uhlemann, Erik G Strom, and Urban Bilstrup. Evaluation of the IEEE 802.11 p MAC Method for Vehicle-to-vehicle Communication. In *Vehicular Technology Conference, 2008. VTC 2008-Fall. IEEE 68th*, pages 1–5. IEEE, 2008.
- [67] M. Boban, T. T V Vinhoza, O.K. Tonguz, and J. Barros. Seeing is Believing Enhancing Message Dissemination in Vehicular Networks Through Visual Cues. *Communications Letters, IEEE*, 16(2):238–241, 2012.
- [68] V. Cabrera, F.J. Ros, and P.M. Ruiz. Simulation-Based Study of Common Issues in VANET Routing Protocols. In *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*, pages 1–5, 2009.
- [69] C. Campolo, H.A. Cozzetti, A. Molinaro, and R. Scopigno. Impact of Urban Radio Obstructions on the Effectiveness of Moving WAVE Providers. In *Wireless Communications and Mobile Computing Conference (IWCMC), 2011 7th International*, pages 1506–1512, 2011.
- [70] B.K. Chaurasia, R.S. Tomar, S. Verma, and G.S. Tomar. Suitability of MANET Routing Protocols for Vehicular Ad Hoc Networks. In *Communication Systems and Network Technologies (CSNT), 2012 International Conference on*, pages 334–338, 2012.

- [71] Marco Conti, Gaia Maselli, Giovanni Turi, and Silvia Giordano. Cross-layering in Mobile Ad Hoc Network Design. *Computer*, 37(2):48–51, 2004.
- [72] LO Djedid, N Lagraa, M Yagoubi, and K Tahari. Adaptation of the MCDS Broadcasting Protocol to VANET Safety Applications. In *Innovations in Information Technology, 2008. IIT 2008. International Conference on*, pages 534–538. IEEE, 2008.
- [73] Djamel Djenouri, Wassim Soualhi, and Elmalik Nekka. VANET’s Mobility Models and Overtaking: An Overview. In *Information and Communication Technologies: From Theory to Applications, 2008. ICTTA 2008. 3rd International Conference on*, pages 1–6. IEEE, 2008.
- [74] S. Durrani, Xiangyun Zhou, and A. Chandra. Effect of Vehicle Mobility on Connectivity of Vehicular Ad Hoc Networks. In *Vehicular Technology Conference Fall (VTC 2010-Fall), 2010 IEEE 72nd*, pages 1–5, 2010.
- [75] M.H. Eiza and Qiang Ni. An Evolving Graph-Based Reliable Routing Scheme for VANETs. *Vehicular Technology, IEEE Transactions on*, 62(4):1493–1504, 2013.
- [76] S.M.A. El-atty and G.K. Stamatiou. Performance Analysis of Multihop Connectivity in VANET. In *Wireless Communication Systems (ISWCS), 2010 7th International Symposium on*, pages 335–339, 2010.
- [77] Holger Füßler, Marc Torrent-Moreno, Matthias Transier, Roland Krüger, Hannes Hartenstein, and Wolfgang Effelsberg. Studying Vehicle Movements on Highways and Their Impact on Ad-hoc Connectivity. *ACM SIGMOBILE Mobile Computing and Communications Review*, 10(4):26–27, 2006.
- [78] M. Fiore, C. Casetti, C. Chiasserini, and D. Borsetti. Persistent Localized Broadcasting in VANETs. *Selected Areas in Communications, IEEE Journal on*, 31(9):480–490, 2013.
- [79] M. Fogue, P. Garrido, F.J. Martinez, J. Cano, C.T. Calafate, and P. Manzoni. An Adaptive System Based on Roadmap Profiling to Enhance Warning Message Dissemination in VANETs. *Networking, IEEE/ACM Transactions on*, 21(3):883–895, 2013.
- [80] Ana Gainaru, Ciprian Dobre, and Valentin Cristea. A Realistic Mobility Model Based on Social Networks for the Simulation of VANETs. In *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*, pages 1–5. IEEE, 2009.

- [81] Mario Gerla, Dario Maggiorini, Claudio E Palazzi, and Armir Bujari. A Survey on Interactive Games over Mobile Networks. *Wireless Communications and Mobile Computing*, 2012.
- [82] Hannes Hartenstein and Kenneth Laberteaux. *VANET: vehicular applications and inter-networking technologies*, volume 1. Wiley Online Library, 2010.
- [83] Christopher Haslett. *Essentials of radio wave propagation*. Cambridge University Press, 2008.
- [84] Xiaoyu Hu, Yu-Dong Yao, Charles Graff, and Trevor Cook. Investigations of Cross-layer Designs for Mobile Ad Hoc Networks. In *Sarnoff Symposium, 2007 IEEE*, pages 1–5. IEEE, 2007.
- [85] Li-Ling Hung, Chih-Yung Chang, Cheng-Chang Chen, and Yu-Chieh Chen. JTEF: Joint Throughput Enhancement and Fairness MAC Protocol for Vehicular Ad Hoc Networks. In *Proceedings of the 6th International Wireless Communications and Mobile Computing Conference*, pages 1–5. ACM, 2010.
- [86] Xin Jin, Weijie Su, and Yan Wei. A Study of the VANET Connectivity by Percolation Theory. In *Consumer Communications and Networking Conference (CCNC), 2011 IEEE*, pages 85–89, 2011.
- [87] Xin Jin, Weijie Su, and YAN Wei. Quantitative Analysis of the VANET Connectivity: Theory and Application. In *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*, pages 1–5. IEEE, 2011.
- [88] Mitsuhsa Kimura, Shinji Inoue, Yoshiaki Kakuda, and Tadashi Dohi. A Route Discovery Method for Alleviating Traffic Congestion Based on VANETs in Urban Transportations Considering a Relation between Vehicle Density and Average Velocity. In *Autonomous Decentralized Systems (ISADS), 2011 10th International Symposium on*, pages 299–302. IEEE, 2011.
- [89] Yen-Cheng Lai, Phone Lin, Wanjiun Liao, and Chung-Min Chen. A Region-Based Clustering Mechanism for Channel Access in Vehicular Ad Hoc Networks. *Selected Areas in Communications, IEEE Journal on*, 29(1):83–93, 2011.

- [90] Kun-chan Lan and Chien-Ming Chou. Realistic Mobility Models for Vehicular Ad hoc Network (VANET) Simulations. In *ITS Telecommunications, 2008. ITST 2008. 8th International Conference on*, pages 362–366. IEEE, 2008.
- [91] Hoa Tung Le and Takeo Fujii. Information Sharing in Sparse Traffic Area by Low Level Carrier Sense for VANET. In *Ubiquitous and Future Networks (ICUFN), 2010 Second International Conference on*, pages 285–290, 2010.
- [92] Myungsub Lee and Changhyeon Park. A Medium Access Mechanism to Reduce Transmission Delay in Ubiquitous Sensor Network. *Journal of Multimedia and Ubiquitous engineering*, 2:491–496, 2012.
- [93] S. Martinez Tornell, E. Hernandez-Orallo, C.T. Calafate, J.-C. Cano, and P. Manzoni. An Analytical Evaluation of a Map-based Sensor-data Delivery Protocol for VANETs. In *World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2013 IEEE 14th International Symposium and Workshops on a*, pages 1–6, 2013.
- [94] Jürgen Maurer, T Fugen, T Schafer, and Werner Wiesbeck. A New Inter-vehicle Communications (IVC) Channel Model. In *Vehicular Technology Conference, 2004. VTC2004-Fall. 2004 IEEE 60th*, volume 1, pages 9–13. IEEE, 2004.
- [95] Hamid Menouar, Fethi Filali, and Massimiliano Lenardi. A Survey and Qualitative Analysis of MAC Protocols for Vehicular Ad Hoc Networks. *Wireless Communications, IEEE*, 13(5):30–35, 2006.
- [96] VK Muhammed Ajeer, PC Neelakantan, and AV Babu. Network connectivity of One-dimensional Vehicular Ad hoc Network. In *Communications and Signal Processing (ICCSP), 2011 International Conference on*, pages 241–245. IEEE, 2011.
- [97] P.S. Nithya Darisini and N.S. Kumari. A Survey of Routing Protocols for VANETs in Urban Scenarios. In *Pattern Recognition, Informatics and Medical Engineering (PRIME), 2013 International Conference on*, pages 464–467, 2013.
- [98] Peyton Z Peebles, Jay Read, and Peter Read. *Probability, random variables, and random signal principles*, volume 3. McGraw-Hill New York, 1987.
- [99] O.M.H. Rehman, H. Bourdouden, and M. Ould-Khaoua. Efficient Alert Messages Dissemination in VANETs using Single-hop Distributed Protocols. In *Wireless and Mobile Networking Conference (WMNC), 2013 6th Joint IFIP*, pages 1–4, 2013.

- [100] M Rudack, M Meincke, and M Lott. On the Dynamics of Ad hoc Networks for Inter Vehicle Communications (IVC). *Citeseer*, 2002.
- [101] Jagruti Sahoo, E Wu, Pratap Kumar Sahu, and Mario Gerla. BPAB: Binary Partition Assisted Emergency Broadcast Protocol for Vehicular Ad Hoc Networks. In *Computer Communications and Networks, 2009. ICCCN 2009. Proceedings of 18th International Conference on*, pages 1–6. IEEE, 2009.
- [102] P.K. Sahu, E.H. Wu, J. Sahoo, and M. Gerla. BAHG: Back-Bone-Assisted Hop Greedy Routing for VANET’s City Environments. *Intelligent Transportation Systems, IEEE Transactions on*, 14(1):199–213, 2013.
- [103] Huijing Shi, Chong Ma, Liang Chen, and Zhizhong Ding. IDVR-PFM: A Connectivity-oriented VANET Routing Protocol in Urban Scenarios. In *Intelligent Control and Information Processing (ICICIP), 2013 Fourth International Conference on*, pages 541–544, 2013.
- [104] Michael Slavik and Imad Mahgoub. Statistical Broadcast Protocol Design for Unreliable Channels in Wireless Ad-hoc Networks. In *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*, pages 1–5. IEEE, 2010.
- [105] Ivan Stojmenovic. *Handbook of wireless networks and mobile computing*, volume 27. John Wiley & Sons, 2003.
- [106] Moahammad M Taghipour, Chong Han, and Mehrdad Dianati. Improving Reliability of Emergency Message Dissemination in VANETs. In *Wireless Communications and Mobile Computing Conference (IWCMC), 2011 7th International*, pages 1200–1205. IEEE, 2011.
- [107] Chai K Toh. *Ad hoc mobile wireless networks: protocols and systems*. Pearson Education, 2001.
- [108] W. Vijitkunsawat and P. Anunvapong. The Multi-Adaptive Routing Protocol for Obstacles and without Obstacles on VANETs. In *Intelligent Transportation Systems (ITSC), 2012 15th International IEEE Conference on*, pages 37–41, 2012.
- [109] Cheng-Xiang Wang, Xiang Cheng, and D Laurensen. Vehicle-to-vehicle Channel Modeling and Measurements: Recent Advances and Future Challenges. *Communications Magazine, IEEE*, 47(11):96–103, 2009.

- [110] Li-Chun Wang, Chung-Wei Wang, and Chuan-Ming Liu. Optimal Number of Clusters in Dense Wireless Sensor Networks: A Cross-Layer Approach. *Vehicular Technology, IEEE Transactions on*, 58(2):966–976, 2009.
- [111] Ruopeng Wang, Jie Zhang, and Xiangyi Zou. Performance Analysis and Optimization of IEEE 802.11 DCF with Constant Contention Window. In *Computing, Communication, Control, and Management, 2008. CCCM '08. ISECS International Colloquium on*, volume 2, pages 407–411, 2008.
- [112] Xin Wang, Changle Li, Lina Zhu, and Chunchun Zhao. An Effective Routing Protocol for Intermittently Connected Vehicular Ad Hoc Networks. In *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, pages 1750–1755, 2013.
- [113] Xue-wen Wu, Shi-ming Song, and Hui-bin Wang. A Novel Position-based Multi-hop Broadcast Protocol for Vehicular Ad Hoc Networks. *Journal of Networks*, 6(1):112–120, 2011.
- [114] Xinsheng Xia, Qingchun Ren, and Qilian Liang. Cross-layer Design for Mobile Ad Hoc Networks: Energy, Throughput and Delay-aware Approach. In *Wireless Communications and Networking Conference, 2006. WCNC 2006. IEEE*, volume 2, pages 770–775. IEEE, 2006.
- [115] Ning Yang, Ravi Sankar, and Jungsik Lee. Improving Ad Hoc Network Performance using Cross-LayCross Information. In *Communications, 2005. ICC 2005. 2005 IEEE International Conference on*, volume 4, pages 2764–2768. IEEE, 2005.
- [116] Jinyun Zhang, Philip V Orlik, Zafer Sahinoglu, Andreas F Molisch, and Patrick Kinney. UWB Systems for Wireless Sensor Networks. *Proceedings of the IEEE*, 97(2):313–331, 2009.
- [117] Jin Zhang, Qian Zhang, and Weijia Jia. VC-MAC: A Cooperative MAC Protocol in Vehicular Networks. *Vehicular Technology, IEEE Transactions on*, 58(3):1561–1571, 2009.
- [118] Jing Zhao and Guohong Cao. VADD: Vehicle-Assisted Data Delivery in Vehicular Ad Hoc Networks. *Vehicular Technology, IEEE Transactions on*, 57(3):1910–1922, 2008.